Saskatchewan
Industry and
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Saskatchewan
Geological Survey

Miscellaneous Report 2003-7

Geology, and Mineral and Petroleum Resources of Saskatchewan

2003

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Cover: Depicts some of the province's mineral resources and related activities, from left to right: ***Top row*** – uranium ore; Deilmann open pit, Key Lake uranium mine. ***Second row*** – first gold brick being poured at Star Lake gold mine; aerial view of Star Lake gold mine; Flin Flon mine and smelter, which has produced copper and zinc since 1930. ***Third row*** – oilfield pumping stations; circular cutting marks of potash mining machines at Esterhazy; conveyor belt carrying potash away from the working face. ***Bottom row:*** dragline operating in stockpiled sodium sulphate at Ormiston sulphate mine; coal-handling facility at Bienfait mine of Estevan Coal Corporation; open-pit coal mining by dragline near Estevan.

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Maps and Chart

Mineral Resource Map of Saskatchewan . . . . back pocket
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Interpretive Geophysical Maps of Saskatchewan . . . . back pocket
Stratigraphic Correlation Chart . . . . back pocket

Introduction

In 2001, the value of Saskatchewan's petroleum and natural-gas sales was $5 billion[1]; mineral sales contributed another $2.4 billion. Saskatchewan leads the world in potash and uranium production, providing about one-third of world production for each of these commodities. Significant untapped potential exists in the province for a variety of minerals, including diamonds, base metals, gold, platinum-group metals, rare-earth elements, clay, silica sand, building stone and brines. Major new petroleum discoveries continue to be made, and new production techniques promise to increase Saskatchewan's petroleum production in the next 25 years. The mineral and energy resource industries are the leading contributor (ahead of agriculture) to the gross domestic product of Saskatchewan.

The purpose of this report is to describe the geology and economic geology of Saskatchewan. This third edition has been substantially updated and restructured. The first part of the report, an overview of the geology of the province, is divided into descriptions of the northern Precambrian Shield, the Phanerozoic sediments that cover the southern two thirds of the province, and the Quaternary glacial deposits. The following 'Economic Geology' part is divided into two sections: 'Energy Resources', including oil, gas and coal; and 'Mineral Resources', including potash, uranium and 15 other commodities. In both sections, information is organized by commodity. In the minerals section, potash and uranium are presented first, based on their economic importance; the remaining commodities follow alphabetically. A colour Mineral Resources Map, in the back pocket, shows the locations of major oil, gas and coal fields, and of mineral occurrences and/or districts. Colour geology, aeromagnetic and gravity maps and a stratigraphic chart are also included in the back pocket.

The 'Geology' chapter of this report synthesizes research by the Saskatchewan Geological Survey, the Saskatchewan Research Council, the Geological Survey of Canada, various university researchers and the mining and petroleum industries. In addition to the preceding sources, the 'Mineral Resources' section of the 'Economic Geology' chapter contains general and specific information on exploration activity, deposit reserves and resources, and mine production, mostly derived from press releases, corporate quarterly and annual reports and corporate websites. Estimates of oil and gas production, and initial and recoverable reserves are taken from the 2001 Reservoir Annual, unless otherwise stated.

The Saskatchewan Geological Survey, part of the Exploration and Geological Services Division of Saskatchewan Industry and Resources (SIR), comprises the Northern Geological Survey and Petroleum Geology branches. The Northern Geological Survey Branch undertakes regional bedrock and surficial geological mapping of the Precambrian Shield of northern Saskatchewan, studies of metallic and industrial minerals (including diamonds), and mineral and oil and gas potential assessments for land-use planning. The Petroleum Geology Branch undertakes geoscience research on Phanerozoic strata covering the southern two-thirds of the province to facilitate exploration and development of the province's petroleum resources. This includes participation in major international projects, such as the current investigation into the behaviour of carbon dioxide after it is injected into an oilfield as part of an enhanced oil recovery program. Most research of the two branches is undertaken in partnership with the Geological Survey of Canada, universities and industry. In some instances, collaborations also involve the geological surveys from neighbouring provinces, territories and states. The Saskatchewan Geological Survey publishes topical research reports and maps, maintains a number of digital databases, and manages sample- and core-examination facilities in Regina for Phanerozoic core and La Ronge for mineral-bearing core. The resident geologist offices in La Ronge and Creighton (part time) monitor the mineral-exploration industry in northern Saskatchewan and provide up-to-date information on exploration and mining activities and opportunities.

There are numerous public sources for current data on Saskatchewan mineral and petroleum resources, sources that provide much more detail than the general level of information presented herein. Current provincial export data can be found at:

http://www.gov.sk.ca/bureau.stats/pea/peaindx2.htm

The best source for current statistics on the oil and gas, and minerals sectors is:

http://www.gov.sk.ca/bureau.stats/ecrvw/er00indx.htm

For mineral deposits, the Saskatchewan Mineral Deposit Inventory is the primary source of information on mineral occurrences in the province; it is a fully searchable, relational database accessible on the SIR website at:

http://www.ir.gov.sk.ca/

The annual publication of Saskatchewan Exploration and Development Highlights is also available on the web, as is the Geological Atlas of Saskatchewan, a fully searchable, multilayered geology map, mineral resource map, and data reference map for the province.

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[1] All values in this report are expressed in Canadian dollars unless otherwise indicated.

Geology

The geology of Saskatchewan can be conveniently divided into two regions. The northern third of the province forms part of the Canadian Precambrian Shield, a vast forested land, dotted with countless lakes and rivers, and containing some of the oldest rocks on earth (*see* block diagram on *Geological Highway Map of Saskatchewan* in back pocket). These old Precambrian rocks underlie all of Saskatchewan; however, in the southern two-thirds of the province, they are covered by much younger (less than 600 million years[2] old), nearly flat-lying sedimentary rocks that were deposited within the Phanerozoic Basin. Several meteorite impact structures have been described in the province, most of which are thought to have resulted from collisions during Cretaceous time. More recently, kimberlitic diatremes of Cretaceous age have been discovered in central Saskatchewan, and indicator minerals suggest their presence elsewhere in the province. Discontinuously overlying both the Precambrian Shield and Phanerozoic Basin are unconsolidated sediments less than 2 Ma in age, which were left behind by the continental ice sheets of the Quaternary period.

Precambrian Shield

The Precambrian Shield of northern Saskatchewan is glacially sculpted and overlain in places by extensive Quaternary glacial deposits. The terrain is variably rugged, forested and lake-strewn, typical of large parts of the Canadian Shield in lower latitudes. Low relief dominates, but it locally reaches over 200 m north of Lake Athabasca. The forest cover opens out to some extent in the northeast, where the Boreal Shield ecoregion gives way to the Taiga Shield. The southern margin of the Precambrian Shield is overlapped by subhorizontal Phanerozoic strata and is generally poorly exposed.

The rocks of the Precambrian Shield are variably exposed and range greatly in metamorphic grade and degree of deformation. The rock record extends discontinuously from about 3.4 Ga (with detrital zircons as old as 3.7 Ga) to about 1.7 Ga, at which time the post-metamorphic, flat-lying Athabasca Group was unconformably deposited. The Precambrian geological history of Saskatchewan is rich but complicated. Several ancient Archean continents, each with its own independent evolutionary story, were welded together and reworked during protracted Paleoproterozoic orogenic events. This orogenic activity led to some of the best preserved Proterozoic volcanic- and continental-arc systems on the planet, and ultimately resulted in the world's largest and richest uranium deposits. The diversity of tectonic elements and age has produced a wide variety of mineral-deposit types, making northern Saskatchewan an excellent target for mineral exploration.

Classification and Subdivision of the Precambrian Shield

All of the exposed Precambrian Shield in northern Saskatchewan is part of the Churchill Structural Province, which was originally defined as a region of rocks yielding K-Ar ages of ca. 1700 Ma, as a result of the Hudsonian Orogeny (Stockwell, 1961). Subsequent U-Pb dating showed that many of the dated rocks within the Churchill Structural Province crystallized during Archean time, but yielded K-Ar ages of ca. 1700 Ma due to a widespread metamorphic event, which ended with subsequent uplift and cooling through the closure temperatures of minerals used in the K-Ar system. The Churchill Structural Province was later divided into the Rae (west side) and Hearne (east side) provinces (Figure 1) along the Snowbird Tectonic Zone, a 3000 km long structural discontinuity that was originally inferred to be a Paleoproterozoic suture (Hoffman, 1988). Subsequent work has cast doubt on this interpretation (e.g., Hanmer, 1997), but the nomenclature persists. In Saskatchewan, the Virgin River and Black Lake shear zones had already been used to divide the dominantly Archean component of the Churchill Structural Province into the Western Craton and Cree Lake Zone (Lewry and Sibbald, 1980), so the new classification simply served to assign new, more nationally accepted names to geological entities that had already been documented within the province. The largely buried Archean Sask Craton was only recently recognized (e.g., Lewry, 1990), but has subsequently been seismically profiled along the Trans-Hudson Orogen Transect of LITHOPROBE (Lucas *et al.*, 1994). The component of the exposed Shield that is dominated by juvenile 1.9 to 1.8 Ga volcanoplutonic-arc rocks and derived clastic assemblages related to the Trans-Hudson Orogen was termed the 'Reindeer Zone' (Stauffer, 1984). The Archean Rae and Hearne provinces are, in part, unconformably overlain by ca. 1.7 Ga, flat-lying sedimentary rocks of the Athabasca Basin (Figure 2).

Further subdivision of this broad, five-fold classification of the exposed Precambrian Shield in Saskatchewan has led to some inconsistencies and confusion over time. Terms such as 'block', 'belt', 'complex' and 'segment' have been historically used either synonymously with 'domain' or separately as subdomains, but these distinctions have been forgotten in many cases. Therefore, the domain classification has been updated so that the term 'domain' is used consistently throughout, at

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[2] Throughout this report, geological ages are expressed as either 'Ma' (millions of years) or 'Ga' (billions of years). Age differences are expressed as 'm.y.'.

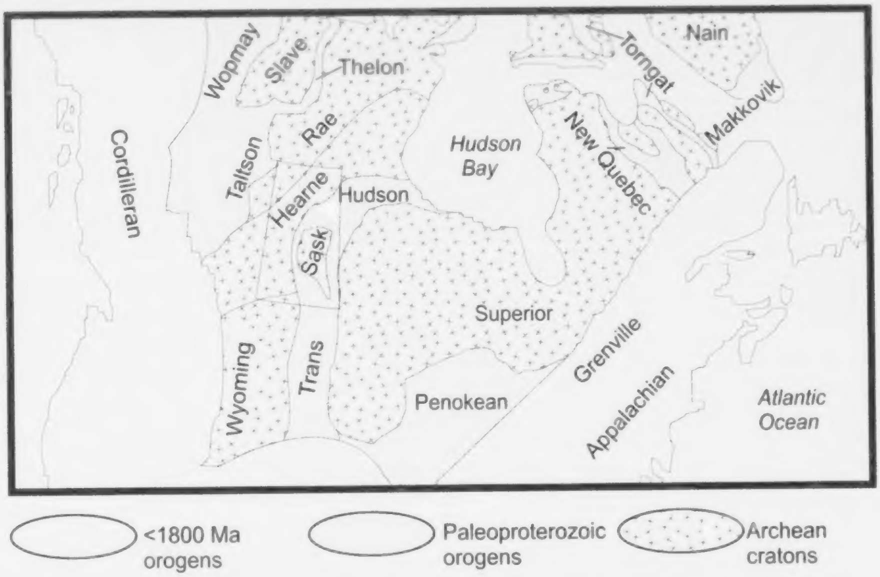


Figure 1 – Orogenic map of North America, with outline indicating location of Saskatchewan (modified from Hoffman, 1988).

the second hierarchical level in the classification scheme (after geological province). In general, a 'lithostructural domain' is defined here as a geographic entity, which is distinguished by a distinct lithological and/or structural character; variations in the intensity of metamorphism are generally not distinguished at this level. These criteria have led to the merging or amalgamation of several small, pre-existing domains (e.g., the former Nevins Lake Block has been incorporated into the Beaverlodge Domain, and the former Black Bay and Forcie domains have been incorporated in the Zemlak Domain), whereas others of questionable merit have been retained for historical reasons (e.g., Glennie and Flin Flon domains), and still others have been modified in areal extent (e.g., Rottenstone Domain). Domain boundaries may be sharp where they are defined by relatively late faults (e.g., Black Bay Fault, Virgin River and Needle Falls shear zones) or transitional, such as the change from dominantly 1.91 to 1.85 Ga volcanoplutonic rocks of the Flin Flon Domain to dominantly 1.85 to 1.83 Ga sedimentary rocks of the adjoining Kisseynew Domain. Such transitional boundaries must be somewhat arbitrarily placed, due to their nature.

It is also important to note that provinces and domains are not tectonic entities; thus, they cannot be involved in collisions. In contrast, a 'craton', which is defined as a relatively stable mass of continental crust (Bates and Jackson, 1987, p. 147), is a geological entity and is capable of colliding with other cratons during periods of intense tectonic activity. Similarly, volcanic arcs, passive margins and foreland basins are geological terms representing distinct tectonic environments, any or all of which may be present within a domain.

With the above definitions in mind, the Precambrian geology of northern Saskatchewan is described under the following headings (Figure 2):

- Rae Province
- Hearne Province
- Sub–Athabasca Group basement
- Sask Province
- Reindeer Zone
- Athabasca Basin
- Post-tectonic features

Rae Province (Previously Western Craton)

The term 'Rae Province' supplants 'Western Craton' (Lewry and Sibbald, 1980), in keeping with the broad lithotectonic classification scheme now in use throughout the rest of Canada, and includes that part of the Shield lying west of the Virgin River and Black Lake shear zones (i.e., the Snowbird Tectonic Zone; Figure 2). It is exposed north and south of the Athabasca Basin and in the central basement uplift of the circular Carswell Structure. Limited information has also been gathered from the basement intervals of drillcore collected in the western Athabasca Basin.

Northern Rae Province (North of the Athabasca Basin)

The large number of domains previously proposed for the northern region (Beck, 1969; Gilboy, 1981; Macdonald, 1983), has been reduced based on

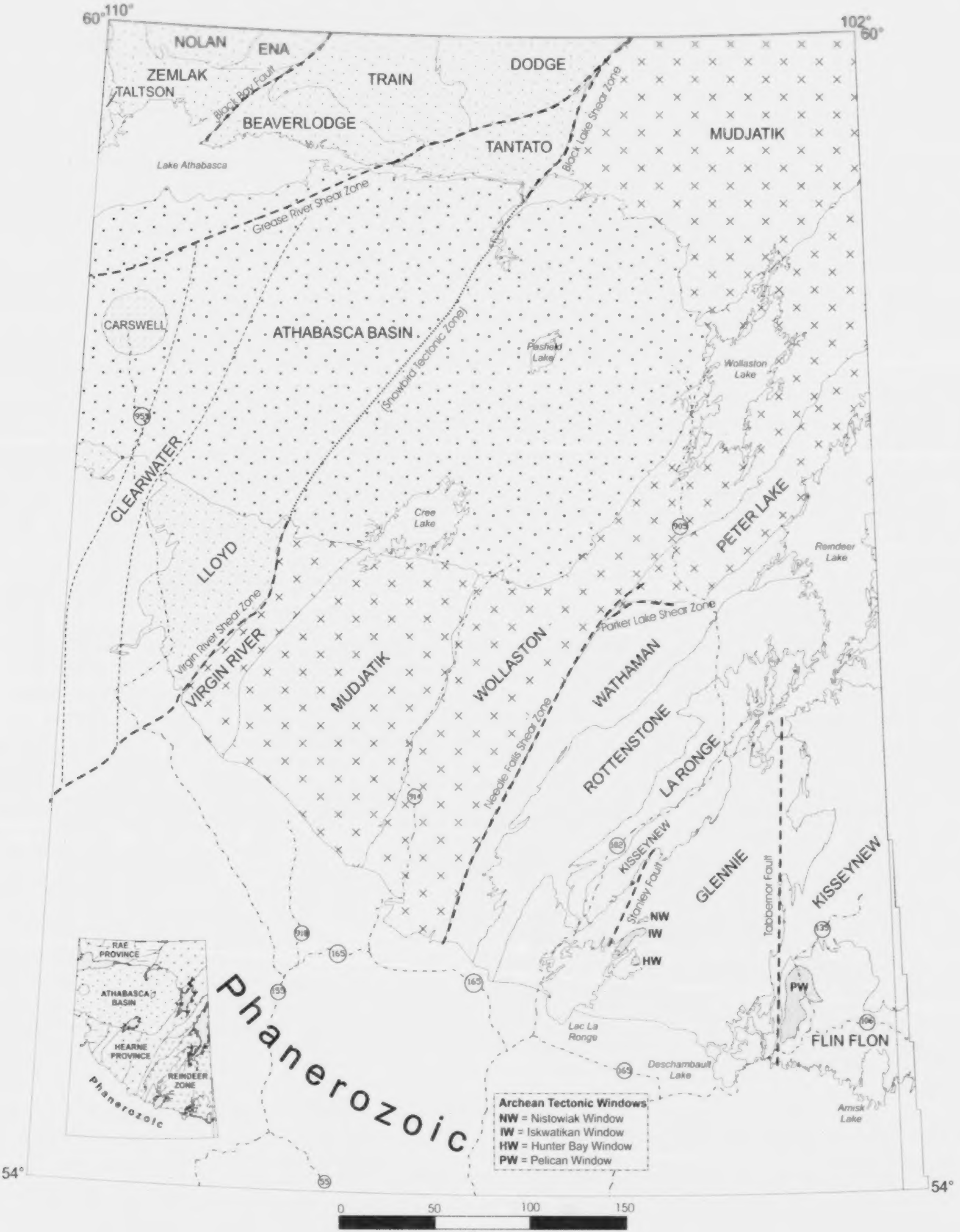

60°
110°
102°
60°
54°
54°
NOLAN
ENA
ZEMLAK
TALTSON
Black Bay Fault
TRAIN
DODGE
BEAVERLODGE
TANTATO
Black Lake Shear Zone
MUDJATIK
Lake Athabasca
Grease River Shear Zone
CARSWELL
ATHABASCA BASIN
(Snowbird Tectonic Zone)
Pasfield Lake
Wollaston Lake
955
CLEARWATER
Cree Lake
905
PETER LAKE
Reindeer Lake
LLOYD
Virgin River Shear Zone
VIRGIN RIVER
MUDJATIK
WOLLASTON
Parker Lake Shear Zone
WATHAMAN
Needle Falls Shear Zone
ROTTENSTONE
LA RONGE
914
102
KISSEYNEW
Stanley Fault
GLENNIE
Tabbernor Fault
KISSEYNEW
NW
IW
HW
135
PW
918
165
155
165
Phanerozoic
Lac La Ronge
106
FLIN FLON
165
Deschambault Lake
Amisk Lake
55
RAE PROVINCE
ATHABASCA BASIN
HEARNE PROVINCE
REINDEER ZONE
Phanerozoic
Archean Tectonic Windows
NW = Nistowiak Window
IW = Iskwatikan Window
HW = Hunter Bay Window
PW = Pelican Window
0
50
100
150
Km

Figure 2 – Geological provinces, lithotectonic domains and major tectonic elements of the Precambrian Shield. Circled numbers are Saskatchewan highway numbers.

lithological correlations during recent mapping (Figure 3; Ashton and Card, 1998; Ashton *et al.*, 2000). The thermotectonic history is best known in the Beaverlodge Domain, but the main sequence of tectonic events applies to the entire region (Figure 4).

Beaverlodge Domain

The Beaverlodge Domain now includes the former 'Nevins Lake Block'. The following brief geological history has been largely put together from the type locality in the Uranium City area, where gold and uranium deposits, together with low metamorphic grades, have focused geological studies since World War II. Geochronological constraints have been provided by Persons (1983) and Hartlaub (pers. comm., 2000). Granitoid basement of ca. 3.05 Ga age (Figure 4) is unconformably overlain by the **Murmac Bay Group** (formerly part of the Tazin Group; includes the Fay Mine Complex), an Archean supracrustal succession comprising a basal polymictic conglomerate, orthoquartzite, basalt, probably comagmatic gabbroic and komatiitic intrusions, dolostone, oxide and silicate facies iron formation, pelite, and extensive psammite to psammopelite. Its age is bracketed by a 2.77 Ga upper intercept age from the youngest detrital zircon (assuming a 1.80 Ga lower intercept related to a metamorphic overprint) and by the intrusive ca. 2.63 Ga Donaldson Lake and Dead Man granites (Hartlaub *et al.*, in press).

A widespread, ca. 2.6 to 2.5 Ga thermotectonic event (D1-M1) locally reached at least upper amphibolite facies conditions and produced the main regional foliation. A second, regional, upper amphibolite to granulite facies event is recorded by 2.36 to 2.28 Ga metamorphic monazite ages and emplacement of ca. 2.32 Ga syn- to postcollisional granites (e.g., Gunnar, Mackintosh Bay and Athona granites). Accompanying D2 deformation resulted in a west-northwest-trending structural fabric defined by isoclinal folds east of Beaverlodge Lake and by the domain-bounding Oldman-Bulyea Shear Zone, which is thought to have developed as a northeast-verging thrust fault ca. 2.4 Ga (Card, 2001b). This Paleoproterozoic D2 event is thought to result from the accretion of exotic terranes to the western margin of the Rae Craton.

Close to tight, northeast-trending D3 folds overprint earlier structures in the east and define the dominant, variably mylonitic structural fabric in the west, adjacent to the Black Bay Fault. Associated metamorphism was sufficient to produce rare anatectic granite sheets (e.g., Box Granite) and more widespread ca. 1.9 Ga zircon

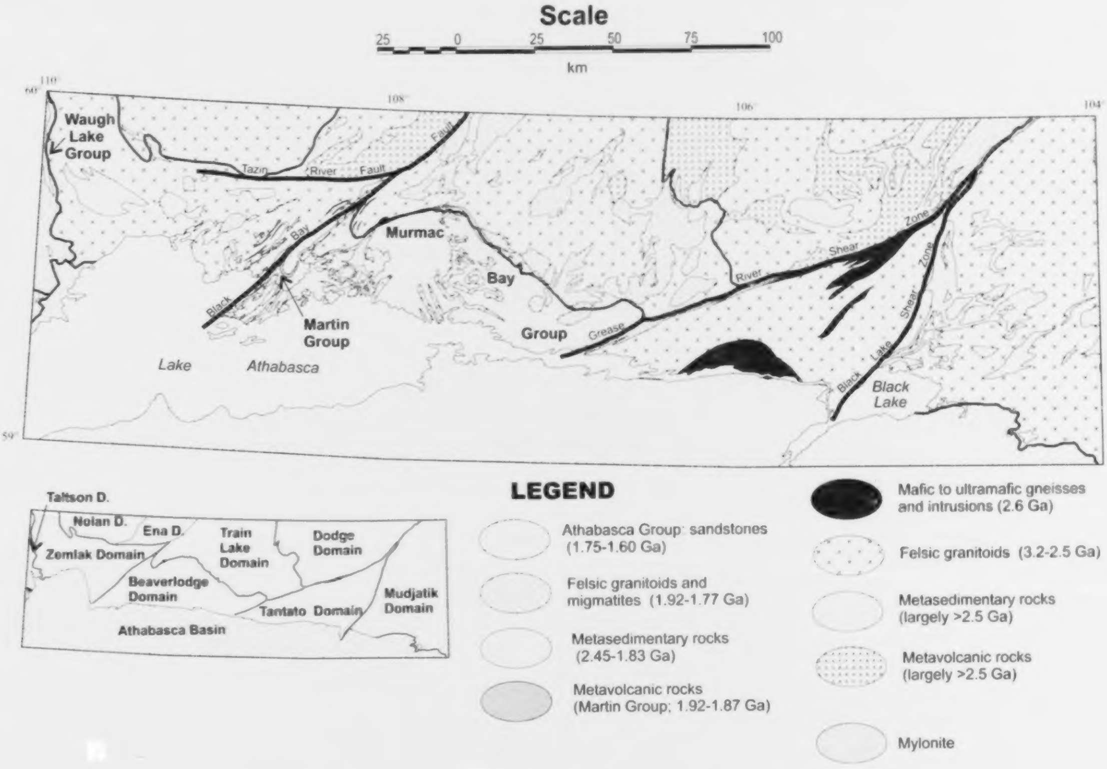

Scale
25
0
25
50
75
100
km
110°
60°
108°
106°
104°
59°
Waugh Lake Group
Tazin River Fault
Fault
Murmac Bay Group
Black Bay
Martin Group
Lake Athabasca
River
Shear Zone
Grease
Black Lake Shear Zone
Black Lake
Taltson D.
Nolan D.
Ena D.
Train Lake Domain
Dodge Domain
Zemlak Domain
Beaverlodge Domain
Tantato Domain
Mudjatik Domain
Athabasca Basin
LEGEND
Athabasca Group: sandstones (1.75-1.60 Ga)
Felsic granitoids and migmatites (1.92-1.77 Ga)
Metasedimentary rocks (2.45-1.83 Ga)
Metavolcanic rocks (Martin Group; 1.92-1.87 Ga)
Mafic to ultramafic gneisses and intrusions (2.6 Ga)
Felsic granitoids (3.2-2.5 Ga)
Metasedimentary rocks (largely >2.5 Ga)
Metavolcanic rocks (largely >2.5 Ga)
Mylonite

Figure 3 – Simplified geology of the Rae Province north of the Athabasca Basin.

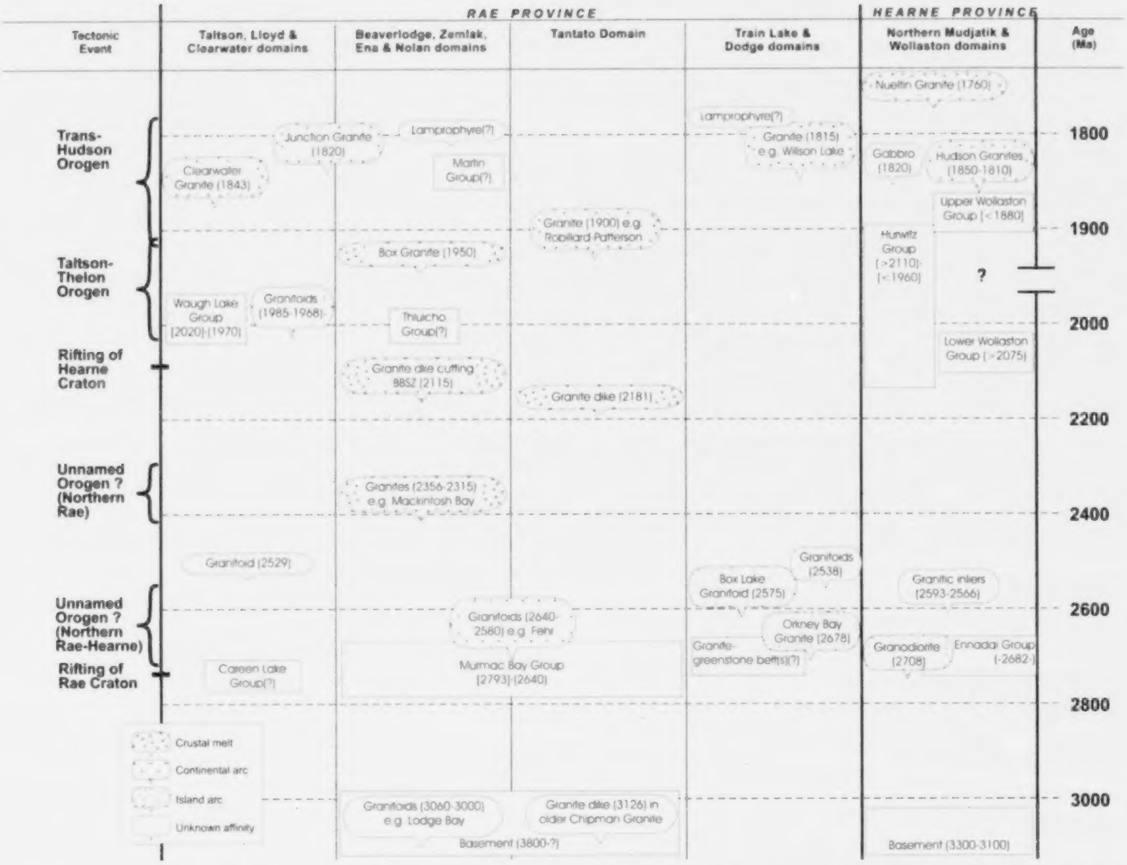

RAE PROVINCE
HEARNE PROVINCE
Tectonic Event
Taltson, Lloyd & Clearwater domains
Beaverlodge, Zemlak, Ena & Nolan domains
Tantato Domain
Train Lake & Dodge domains
Northern Mudjatik & Wollaston domains
Age (Ma)
Trans-Hudson Orogen
Taltson-Thelon Orogen
Rifting of Hearne Craton
Unnamed Orogen ? (Northern Rae)
Unnamed Orogen ? (Northern Rae-Hearne)
Rifting of Rae Craton
Nueltin Granite (1760)
Lamprophyre(?)
Junction Granite (1820)
Lamprophyre(?)
Granite (1815) e.g. Wilson Lake
1800
Clearwater Granite (1843)
Martin Group(?)
Gabbro (1820)
Hudson Granites (1850-1810)
Upper Wollaston Group [<1880]
Granite (1900) e.g. Robillard-Patterson
1900
Box Granite (1950)
Hurwitz Group [>2110]-[<1960]
?
Waugh Lake Group [2020]-[1970]
Granitoids (1985-1968)
Thluicho Group(?)
2000
Lower Wollaston Group [>2075]
Granite dike cutting BBSZ (2115)
Granite dike (2181)
2200
Granites (2356-2315) e.g. Mackintosh Bay
2400
Granitoid (2529)
Granitoids (2538)
Box Lake Granitoid (2575)
Granitic inliers (2593-2566)
Granitoids (2640-2580) e.g. Fehr
2600
Orkney Bay Granite (2678)
Granite-greenstone belt(s)(?)
Granodiorite (2708)
Ennadai Group (-2682-)
Careen Lake Group(?)
Murmac Bay Group [2793]-[2640]
2800
Crustal melt
Continental arc
Island arc
Unknown affinity
Granitoids (3060-3000) e.g. Lodge Bay
Granite dike (3126) in older Chipman Granite
3000
Basement (3800-?)
Basement (3300-3100)

Figure 4 – Lithostructural history of the Rae and northern Hearne provinces. Ages in square brackets are based on detrital zircon study; round brackets denote igneous ages. References for age constraints can be found in the text. Abbreviation: BBSZ, Black Bay Shear Zone.

and titanite growth. This D3 thermotectonic event probably resulted from collision with the Slave Craton during the ca. 2.0 to 1.9 Ga Taltson-Thelon Orogen, which apparently ended a protracted period of terrane accretion to the western Rae Craton margin.

Deposition of the virtually unmetamorphosed Paleoproterozoic Martin Group redbeds is thought to have taken place in a postorogenic (Taltson-Thelon) collisional basin, which is best preserved on the downdropped eastern block of the Black Bay Fault. Late east- and south-side-down normal faulting along a conjugate set has also preserved Archean rocks, in parts of the western Beaverlodge Domain, that have never been metamorphosed above greenschist to lower amphibolite facies. Late D4 deformation produced open north-trending folds and widespread brittle-ductile deformation, including the conjugate set of shear fractures along which late southeast-trending diabase and ≥1.78 Ga (Card, 2001b) northeast-trending lamprophyre dike sets have been emplaced. The diabase dikes intrude the lowermost units of the Martin Group and may have been feeders to the Martin basalts. Their broad age relationships and orientation suggest a possible correlation with the 1.827 Ga Sparrow Dikes of the Taltson Magmatic Zone to the northwest (Bostock and van Breeman, 1992). The lamprophyres have the same temporal relationships and geochemical affinities as lamprophyres associated with the 1.85 to 1.80 Ga Christopher Island Formation of the Dubawnt Group in the Baker Lake area of Nunavut (LeCheminant *et al.*, 1987). The vein-type uranium mineralization of the Beaverlodge mining camp was also largely deposited in this D3-D4 fracture system, and has yielded ca. 1.78 Ga pitchblende ages (Koeppel, 1968). The D4 event is attributed to amalgamation of the Rae-Hearne, Sask and Superior cratons during the 1.9 to 1.8 Ga Trans-Hudson Orogen.

East of Uranium City in the former Nevins Lake Block, the metamorphic grade gradually increases eastward and northeastward to granulite facies. In addition to the typical Archean Murmac Bay Group succession seen at

Uranium City, the eastern Beaverlodge Domain includes a larger component of migmatitic to diatexitic pelites, possibly representing a deeper water facies.

Zemlak Domain

West of the Black Bay Fault, where the former Black Bay and Forcie domains have been incorporated into the Zemlak Domain (Figure 2), the intensity of metamorphism increases westward from upper amphibolite to granulite facies, and the rocks are variably mylonitized. Distinctive rock types of the Archean Murmac Bay Group (i.e., quartzite, amphibolite and pelite) constitute about 20% of the domain, which is dominated by quartzofeldspathic gneisses and migmatites. Many of these are probably highly deformed and metamorphosed equivalents of psammitic to psammopelitic rocks of the Murmac Bay Group, but most appear to be variably magnetic orthogneisses, presumably derived from 2.63 to 2.32 Ga and other, unidentified granitoid suites of the basement. Although this broad stratigraphic framework is similar to that of the Beaverlodge Domain, the Zemlak Domain remains distinct because 1) the age and nature of the dominant quartzofeldspathic rocks is poorly known; and 2) the more intense D2 and D3 deformation has left both the Murmac Bay Group and the undifferentiated quartzofeldspathic gneisses variably mylonitized. This more intense early deformation likely records terrane accretion to the western Rae Craton margin, and suggests that rocks of the Zemlak Domain were at a deeper crustal level than those of the Beaverlodge Domain immediately east of the Black Bay Fault. The greenschist facies **Thluicho Lake Group**, comprising basal conglomerate, feldspathic arenite and argillite, unconformably overlies the variably mylonitized Archean basement, but has been deformed by northeast-trending D3 folds. The Thluicho Lake Group is in turn unconformably overlain by the less deformed Ellis Bay 'felsic breccias' and Martin Group redbeds, which have only been subjected to D4 deformation (Scott, 1978). The syn- to post-Martin diabase dikes described in the Beaverlodge Domain are even more common in the Zemlak Domain, where they trend east to southeast and reach up to 100 m in thickness. They have also been deformed by the D4 event.

Taltson Domain

West of the Zemlak Domain, along the Saskatchewan-Alberta boundary, lower greenschist facies sandstones, mudstones and volcanic rocks of the 2.02 to 1.97 Ga **Waugh Lake Group** are intruded by the 1.97 to 1.96 Ga Colin Lake and Wylie Lake subduction-related granitoids of the Taltson Magmatic Zone (Figures 3, 4; McDonough *et al.*, 1995; McDonough and McNicoll, 1997). The north-trending deformational front attributed to the 2.0 to 1.9 Ga Taltson-Thelon Orogen appears to rotate or truncate earlier east-trending D2(?) structures on regional aeromagnetic maps (unpublished aeromagnetic data, Geological Survey of Canada).

Nolan Domain

The Nolan Domain (formerly Nolan Block) contains minor quartzofeldspathic migmatite similar to that in the Zemlak Domain, but is dominated by 2.64 to 2.58 Ga (Van Schmus *et al.*, 1986) granitic to dioritic plutonic rocks (Figure 3; Koster, 1970). Potassium-argon dates of ca. 2.37 Ga (Koster and Baadsgaard, 1970) record cooling after a major granulite facies metamorphic event. A northwest-trending S2(?) foliation within the domain was probably established at this time, and later truncated and variably overprinted during subsequent Paleoproterozoic events. Regional aeromagnetic maps indicate considerable magnetic and structural heterogeneity, which is not yet fully understood.

Ena Domain

The Ena Domain is bounded by the Nolan Domain granitoids and the Tazin River and Black Bay faults (Figure 3). Quartzofeldspathic gneisses and migmatites in the west are similar to those of the Zemlak Domain (Koster, 1970), but the Ena Domain has been distinguished due to the abundance of granulite facies, intermediate to mafic gneisses in the east (Koster, 1965).

Train Lake Domain

East of the Black Bay Fault and north of the Beaverlodge Domain, the Train Lake Domain (Figure 3) is characterized by high magnetic and low gravity signatures. It comprises subordinate upper amphibolite to granulite facies, amphibolite-pelite supracrustal belts within extensive migmatitic orthogneisses that display arc-type geochemical affinities (Ashton *et al.*, 1999a). A quartz monzodiorite intruding amphibolite within one of the supracrustal belts, and a gneissic leucogranite from the orthogneiss, have yielded preliminary U-Pb zircon ages of 2.57 Ga (Ashton *et al.*, 1999a) and 2.54 Ga (Card, 2001b), respectively (Figure 4). A ca. 1.815 Ga metamorphic overprint is inferred from the lower intercept age of the former, together with a monazite age from amphibolite. Broadly coeval, highly radiometric granite sheets and plutons are common throughout the domain and are believed to be part of the 1.85 to 1.81 Ga Hudson granitoid suite (Peterson and van Breeman, 2002). The 1.815 Ga Willson Lake Granite stitches the Oldman-Bulyea Shear Zone, along which rocks of the Beaverlodge Domain have been thrust over those of the Train Lake Domain, although an inferred syntectonic, ca. 2.41 Ga mylonitized aplite within the zone suggests that initial displacement was much earlier (Card, 2001b). The >1.78 Ga lamprophyre dike swarm of the Beaverlodge Domain extends across the Oldman-Bulyea Shear Zone into the Train Lake Domain, but there are far fewer dikes. Farther north, the Beaverlodge–Train Lake domain contact is a folded mylonite zone (Hartlaub, 1999). To date, no evidence of the 2.3 Ga thermotectonic event has been found east of the Beaverlodge Domain. Similarly, the 1.9 Ga event has not been recognized in the Train Lake Domain, in spite of its dominant role both to the east and to the west.

Dodge Domain

Although the Dodge Domain is at least locally in tectonic contact with the Train Lake Domain to the west (Ashton and Card, 1998), the main difference in the former appears to be the larger component of amphibolitic and pelitic supracrustal rocks (Figure 3). Most rocks have been metamorphosed to granulite facies but later subjected to a strong, upper amphibolite facies overprint. A foliated granite intruding amphibolite at Scott Lake has yielded a preliminary U-Pb zircon age of 2.68 Ga, establishing a minimum age for the supracrustal succession (Ashton *et al.*, 1999a). The similarity of this result to the 2.708 to 2.682 Ga ages for volcanic and granitic rocks of the Ennadai-Rankin Greenstone Belt in the Mudjatik Domain (Hearne Craton) to the east (Figure 4; Chiarenzelli and Macdonald, 1986; Delaney *et al.*, 1990; Reilly, 1993b) may indicate that Archean rocks were broadly correlative in this part of the Rae and Hearne provinces prior to displacements along the younger Snowbird Tectonic Zone. A lower intercept age of 1.93 Ga (Ashton *et al.*, 1999a) is similar to high-pressure metamorphic ages obtained in the Tantato Domain (Baldwin *et al.*, 2000), which are attributed to the Taltson-Thelon Orogen. Rare lamprophyre dikes of the >1.78 Ga swarm are also present.

Tantato Domain

The Tantato Domain (Figure 3; East Athabasca Mylonite Triangle of Hanmer, 1997) includes the ca. 3.4 Ga Chipman Batholith, extensive pelitic diatexite and mafic rocks, and a variety of ca. 2.63 to 2.58 Ga granitoids (Figure 4; Hanmer, 1997). Virtually all of these rocks have been metamorphosed to granulite facies and have been variably mylonitized. The age of mylonitization was originally thought to be ca. 2.6 Ga (Hanmer, 1997), although there is increasing evidence that much of this high strain coincided with a ca. 1.9 Ga high-pressure (>10 kbar) metamorphic event (Mahan *et al.*, 2001a, b; Flowers *et al.*, 2002). The Tantato Domain has been interpreted as the northern end of a tectonic 'lozenge' lying west of the Snowbird Tectonic Zone (e.g., Hanmer *et al.*, 1994), although aeromagnetic evidence to the south indicates that the 'lozenge' is open ended to the west and therefore an integral part of the Rae Province (Figure 5; Card, 2001a). The western Tantato Domain is in fault contact with the Beaverlodge Domain, with which it has noteworthy compositional, temporal and metamorphic similarities (Williams and Jercinovic, 2000; Williams *et al.*, 2000), and with the Dodge and Train Lake domains, along the 1.9 to 1.8 Ga greenschist facies Grease River Shear Zone (Lafrance *et al.*, 1999). Together with its orientation and the widespread preservation of granulite facies rocks to the west, the 1.9 Ga thermotectonic event suggests that the Black Lake Shear Zone segment (Legs Lake Shear Zone of Mahan and Williams, 2002) of the Snowbird Tectonic Zone formed as a west-side-up, high-angle reverse, intracratonic fault (Mahan and Williams, 2002). It was probably initiated in response to the 2.0 to 1.9 Ga collision of the Slave Craton with the Rae Craton during the Thelon Orogen (Gibb, 1978), although displacements as late as 1.87 to 1.84 Ga indicate a possible overlap with tectonism related to the Trans-Hudson Orogen (Mahan and Williams, 2002).

Southern Rae Province (South of the Athabasca Basin)

Lloyd Domain

South of the Athabasca Basin, the Rae Province has historically been divided into the Western Granulite, Clearwater and Firebag domains (Lewry and Sibbald, 1977), of which only the first is well exposed. On the basis of a distinctive, alternating, high and low aeromagnetic signature, however, the Western Granulite and Firebag segments appear to have been continuous and correlative prior to development of an overprinting, northeast-trending aeromagnetic high that marks the Clearwater Domain (Figure 5). For this reason, the former Western Granulite and Firebag domains have been amalgamated to form the Lloyd Domain.

The Lloyd Domain (Figure 6) comprises variably retrogressed, granulite facies charnockitic to noritic gneisses (many of which are characterized by blue quartz), subordinate quartzite and psammitic to pelitic paragneiss, and the Clearwater Anorthosite Complex (Lewry and Sibbald, 1977). Samarium-neodymium ages of 3.5 to 2.8 Ga indicate an Archean origin for many of the granulite facies gneisses, and U-Pb and Rb-Sr data suggest major thermotectonic events, at 2.3 to 2.2 Ga and 2.1 to 1.9 Ga, that are tentatively attributed to terrane accretion at the western margin of the Rae Craton (Crocker *et al.*, 1993; Bickford *et al.*, 1994). An earliest gneissosity is defined by granulite facies parageneses that are thought to have formed during the 2.3 to 1.9 Ga interval. Dioritic to granitic intrusions of ca. 1.98 Ga, from immediately west of the Virgin River Shear Zone at Careen Lake, indicate that arc-type plutons of the Taltson Magmatic Zone extend throughout the Lloyd Domain (R. Stern, pers. comm., 2002).

This early fabric varies from northwest trending in the west to northeast trending in the east, where it is overprinted by a lower amphibolite facies, northeast-trending mylonitic fabric associated with the Virgin River Shear Zone (Lewry and Sibbald, 1977; Bickford *et al.*, 1994). West-plunging, down-dip stretching lineations, together with a variety of kinematic indicators, suggest that the earliest recognized deformation in the Virgin River Shear Zone involved east-vergent thrusting (Bickford *et al.*, 1994; Card, 2002). The presence of these earliest down-dip stretching lineations in ca. 1.98 Ga dioritic rocks, together with crosscutting of the mylonites by the weakly deformed, ca. 1.82 Ga

Junction Granite, constrain this early thrusting to the 1.98 to 1.82 Ga range, and suggest that the Virgin River Shear Zone formed in response to the Taltson-Thelon Orogen. Younger, gently northeast- and southwest-plunging stretching lineations and related kinematic indicators infer a dextral overprint, resulting at least in part from the Trans-Hudson Orogen. Variably tight, northeast-trending folds with gently north-northeast- to south-southwest-plunging axes are considered broadly synchronous with the shearing events. Rare 1.87 to 1.81 Ga sensitive high-resolution ion microprobe (SHRIMP; Crocker *et al.*, 1993) data may record weak metamorphic overprinting during the Trans-Hudson Orogen.

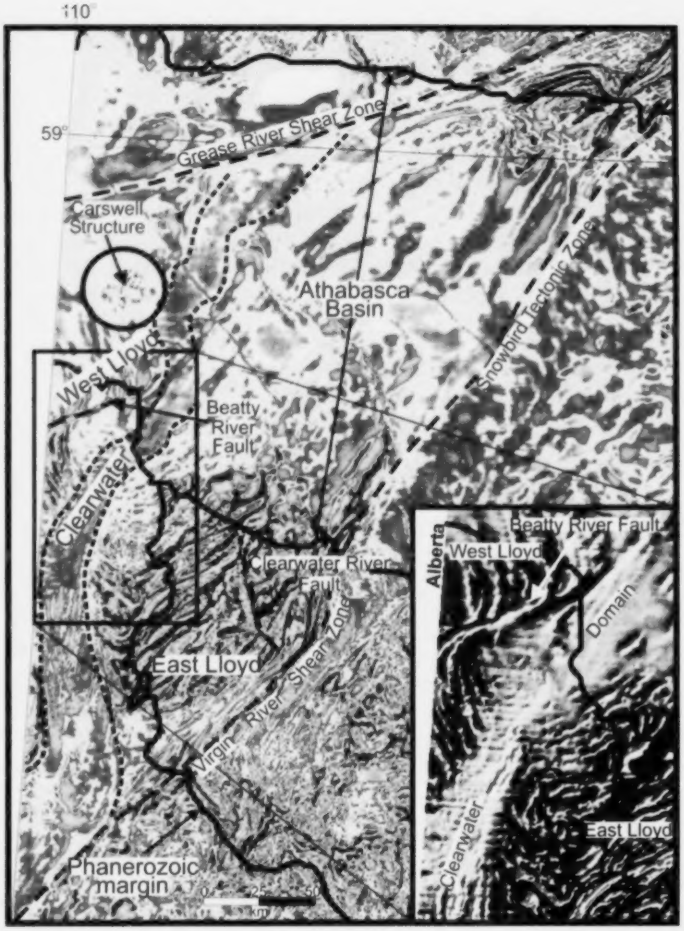


Figure 5 – First vertical magnetic derivative aeromagnetic map of the exposed, sub-Athabasca and sub-Phanerozoic southern Rae Province, showing magnetic structure and dominant tectonic elements. Inset is a shadowgram that shows overprint of early, northwest-trending Lloyd Domain structures by younger north-northeast-trending structures of the Clearwater Domain. Note apparent right-lateral ductile displacement of early Lloyd Domain structures along the Beatty River Fault.

The **Clearwater Anorthosite Complex** is located near the eastern margin of the domain and is a layered, cumulate, anorthosite to gabbro series that is dominated by noritic anorthosite (Hulbert, 1987). Independent studies have yielded inconsistent Sm-Nd isochron ages of ca. 2.48 Ga (Hulbert, 1988) and 1.85 Ga (Crocker *et al.*, 1993), together with depleted-mantle model ages (T_{DM}) between 2.67 and 2.03 Ga (Crocker *et al.*, 1993), consistent with the suggestion that there may be two ages of anorthositic rocks. Recent studies have yielded 1908 ± 2 Ma U-Pb zircon (Heaman *et al.*, 1999) and 1917 ± 7 Ma $^{40}Ar/^{39}Ar$ ages (Halls and Hanes, 1999), which are thought to record a younger metamorphic overprint.

The distinctive, alternating, high and low aeromagnetic pattern of the exposed Lloyd Domain extends northwestward under the Athabasca Basin, where it is dextrally displaced along the Beatty River Fault before dying out around the Carswell Structure (Figure 5), perhaps due to thickening Athabasca Group cover. The central basement uplift of the Carswell Structure is poorly exposed in outcrop but is known from open pits and drillcore to comprise roughly equal proportions of upper amphibolite to granulite facies, red orthogneiss and quartzofeldspathic paragneiss, including quartzite and psammitic to psammopelitic gneiss with subordinate pelitic migmatite to diatexite, rare oxide to silicate facies iron formation, and coarse-grained mafic to ultramafic rocks (Harper, 1982). This supracrustal succession is broadly similar both to that of the exposed Lloyd Domain and to the Murmac Bay Group of the Rae Province north of Lake Athabasca. Pegmatitic rocks are common as anatectic sheets within the paragneiss.

Uranium-lead analysis of two quartzofeldspathic gneisses of unknown origin has yielded ages of 2.32 and 2.13 Ga (Bell, 1985), which coincide with the timing of granitoid intrusions in the Beaverlodge Domain and with thermotectonism in the exposed Lloyd Domain. Rubidium-strontium studies have also produced evidence for a ca. 2.30 Ga thermotectonic event (Bell and Blenkinsop, 1980), as well as metamorphic ages in the 2.00 to 1.75 Ga range.

Three phases of ductile deformation were documented in the metamorphosed core of the Carswell Structure (Harper, 1982). An S1 gneissic foliation is isoclinally folded about gently plunging F2 axes. The D3 deformation is characterized by open, doubly plunging folds with north-trending, steeply dipping axial surfaces.

Brittle deformation associated with the D3 event overprints the upper amphibolite to granulite facies assemblages formed during D1 and possibly D2. Deformation associated with the Carswell meteorite impact resulted in about 2 km of basement uplift and widespread cataclasis.

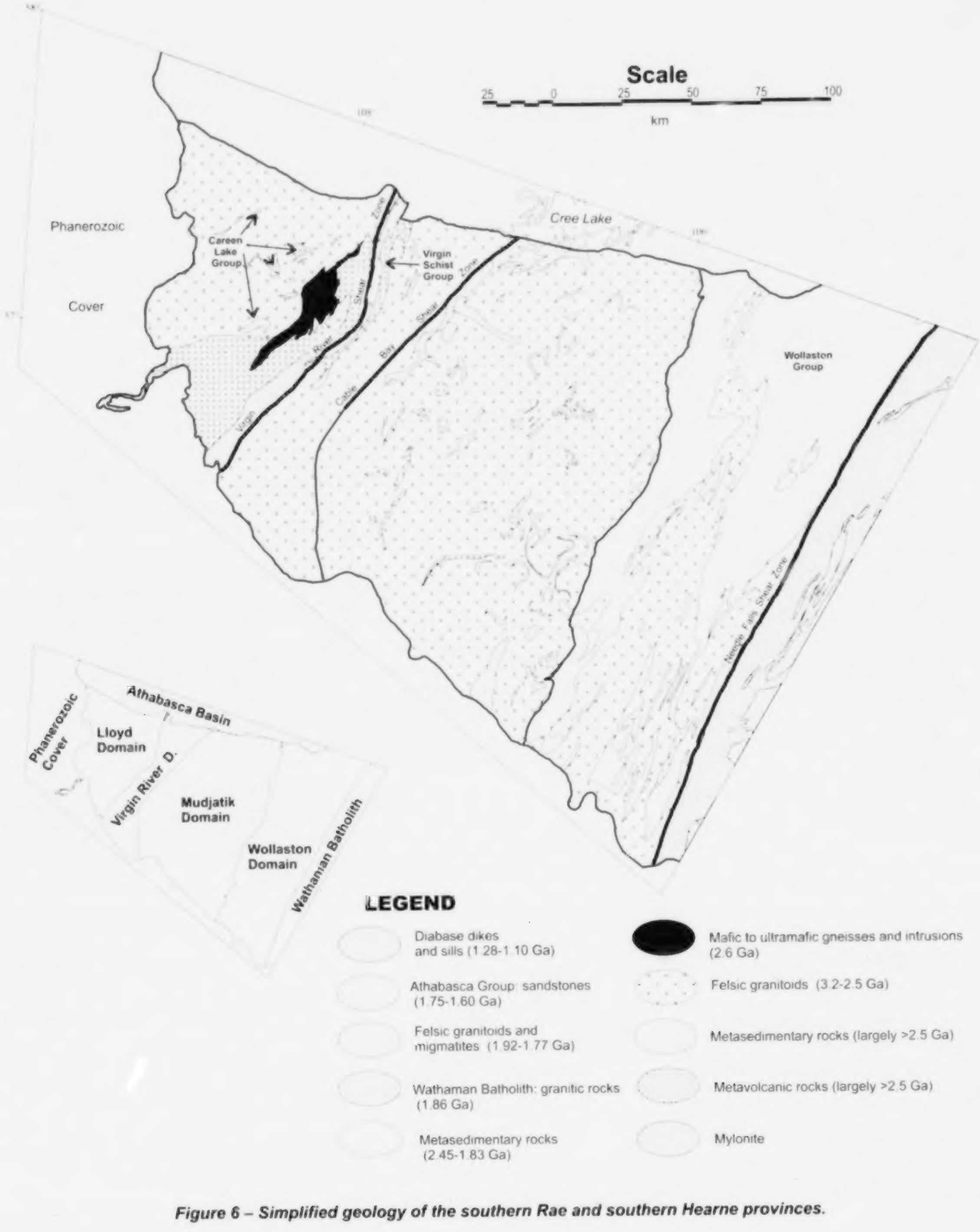

Scale
25
0
25
50
75
100
km
Phanerozoic
Cover
Careen Lake Group
Virgin Schist Group
Virgin River Shear Zone
Cable Bay Shear Zone
Cree Lake
Wollaston Group
Needle Falls Shear Zone
Athabasca Basin
Phanerozoic Cover
Lloyd Domain
Virgin River D.
Mudjatik Domain
Wollaston Domain
Wathaman Batholith
LEGEND
Diabase dikes and sills (1.28-1.10 Ga)
Athabasca Group: sandstones (1.75-1.60 Ga)
Felsic granitoids and migmatites (1.92-1.77 Ga)
Wathaman Batholith: granitic rocks (1.86 Ga)
Metasedimentary rocks (2.45-1.83 Ga)
Mafic to ultramafic gneisses and intrusions (2.6 Ga)
Felsic granitoids (3.2-2.5 Ga)
Metasedimentary rocks (largely >2.5 Ga)
Metavolcanic rocks (largely >2.5 Ga)
Mylonite

Figure 6 – Simplified geology of the southern Rae and southern Hearne provinces.

Two sets of late ductile to brittle faults are prominent throughout the southern Rae Province. A dextral, northeast-trending set (e.g., the Beatty River Fault) parallels the Grease River Shear Zone in the north and likely results from the Taltson-Thelon Orogen. Apparent displacement of a ca. 1.27 Ga Mackenzie dike by this fault set (Figure 5) suggests a long history of reactivation (LeCheminant and Heaman, 1989). The second prominent fault set trends north-northwest (Figure 5) and is probably time equivalent to the Tabbernor Fault system.

Drillcore from the extrapolated northwestern extension of the alternating high and low aeromagnetic signature northwestward into Alberta (Figure 5) contains granitoid rocks, two of which have yielded preliminary SHRIMP ages of ca. 1.97 Ga (R. Stern, pers. comm., 2002). Consequently, they have been correlated with the ca. 1.963 Ga Wylie Lake Suite, exposed north of Lake Athabasca (Wilson, 1986). The distinctive aeromagnetic pattern therefore is thought to result from a heterogeneous mix of ≥2.3 Ga magnetiferous orthogneiss with weakly to nonmagnetic Archean supracrustal and Taltson arc rocks.

Clearwater Domain

The Clearwater Domain is dominated by a 20 to 30 km wide, north- to north-northeast-trending, positive aeromagnetic anomaly, which crosscuts the regional aeromagnetic fabric of the Lloyd Domain. The domain extends southward from the Grease River Shear Zone in the north to the Snowbird Tectonic Zone in the south, where it appears to be truncated and dextrally displaced (Figure 5). The only exposure within the Clearwater magnetic high is along the Clearwater River, where the 1.84 Ga (R. Stern *et al.*, pers. comm., 2002) Clearwater Granite intrudes multiply deformed felsic gneiss (Figure 4). The Clearwater Granite is similar in appearance, relative age and magnetic signature to the ca. 1.82 Ga (Bickford *et al.*, 1994) Junction Granite (Lewry and Sibbald, 1977), which was emplaced late in the deformational history of the Virgin River Shear Zone.

The S1 foliation in the older felsic gneiss is deformed by north-trending F2 folds and by east-trending F3 folds with axial surfaces that dip steeply to the south (Lewry and Sibbald, 1977). The north-trending D2 deformation is presumably responsible for the crosscutting, coplanar aeromagnetic fabric, which parallels the margins of the Clearwater Domain. The dearth of magnetite in the Clearwater Granite suggests that the aeromagnetic high is associated with the highly strained host felsic gneisses. Assuming this D2 strain predates the 1.84 Ga Clearwater Granite, it is probably related to the Virgin River Shear Zone and ultimately to the ca. 1.9 Ga Taltson-Thelon Orogen.

Synthesis of the Rae Province

The oldest rocks in the Rae Province represent 3.7 to 2.8 Ga basement, which is known from exposed ca. 3.0 Ga granitoid rocks and detrital zircons in the Beaverlodge Domain and from Nd model ages both north and south of the Athabasca Basin. This Paleoarchean to Mesoarchean basement is unconformably overlain by the Murmac Bay Group, a rift-type, dominantly sedimentary succession that may mark the opening of a Neoarchean ocean. Although the Murmac Bay Group is best known in the north, supracrustal remnants found throughout much of the Rae Province are lithologically similar and presumed to be correlative. A 2.68 Ga oceanic granite-greenstone–type suite in the Dodge Domain is broadly similar to, and perhaps correlative with, rocks of the ca. 2.7 Ga Ennadai-Rankin Belt in the Hearne Province. The widespread suite of 2.62 to 2.58 Ga granitoid rocks spanning the Rae-Hearne boundary exhibit arc-like geochemical affinities, and may record subduction under a proto–Rae-Hearne Craton. The ca. 2.57 to 2.53 Ga granitoids of the Train Lake Domain could mark the tail end of that event or mark accretion of the ca. 2.70 Ga Ennadai-Rankin Belt (Figure 4), since it appears devoid of the 2.62 to 2.58 Ga granitoid suite (Davis *et al.*, 2000b).

A variety of 2.4 to 1.9 Ga granitoid rocks and broadly coeval thermotectonic events at 2.36 to 2.28 Ga and 2.0 to 1.85 Ga indicate a long period of active tectonism in the southwestern Rae Province. This intrusive suite has been attributed elsewhere to rifting and continental break-up (McNicoll *et al.*, 2000), but the composition and extent of the dominant ca. 2.3 Ga granites, together with the widespread thermotectonic reworking, suggest that it more likely resulted from terrane accretion at the western Rae Craton margin (Bostock and van Breeman, 1994). Minor 2.1 Ga granitic dikes and sheets are similarly coeval with the dominant arc(?) magmatism of the outboard Chinchaga magnetic high, located farther west under Phanerozoic cover in Alberta (Ross *et al.*, 1991). It is unclear whether these early events resulted from the accretion of currently unrecognized microplates or a more complicated scenario, but subsequent widespread 1.99 to 1.93 Ga arc and collisional granitoids (Figures 4, 7), together with a 1.93 to 1.90 Ga thermotectonic event, are together attributed to accretion of the Buffalo Head Terrane and Slave Craton to the Rae Craton during the Taltson-Thelon Orogen. Younger terrane accretion to the west during the 1.95 to 1.84 Ga Wopmay Orogen (Hoffman, 1988) may have prolonged or rejuvenated this thermotectonic event. Although it may have begun earlier, the dominant northeast-trending structural fabric (including features such as the Snowbird Tectonic Zone and Black Bay Shear Zone) is largely attributed to this ca. 1.9 Ga event.

The 1.92 to 1.80 Ga Trans-Hudson Orogen strongly reworked Archean rocks of the Hearne Province, but ca. 1.815 Ga granites and rare metamorphic monazite dates indicate that its effects also extended into the eastern Rae Province. The significant temporal overlap of orogenic activity on the western and eastern margins of the Rae-Hearne Craton produced a vise-like stress regime by about 1.86 Ga. Thus, deformational fabrics created or modified after that time, including the dominant northeast-trending regional fabric and the network of crosscutting ductile to brittle faults, must be considered composite in origin.

Snowbird Tectonic Zone

The Snowbird Tectonic Zone is a northeast-trending zone marked by a linear aeromagnetic anomaly that extends nearly 3000 km from the Rocky Mountain deformational front in the Alberta basement to central Nunavut (Figure 1). The zone was originally interpreted as a suture marking the inferred Paleoproterozoic collision of the Rae and Hearne cratons (Walcott and Boyd, 1971; Gibb and Halliday, 1974; Hoffman, 1988), although recent work suggests that the Rae and Hearne provinces were juxtaposed prior to 2.6 Ga (e.g., Davis *et al.*, 2000b). In Saskatchewan, the exposed part of the Snowbird Tectonic Zone comprises the Black Lake Shear Zone (Legs Lake Shear Zone of Mahan *et al.*, 2001a, b) north of the Athabasca Basin (Figures 2, 3) and the Virgin River Shear Zone to the south (Figures 2, 3, 6).

Along the Black Lake Shear Zone, high-pressure (≥10 kbar) granulite facies mylonitic rocks of the Tantato Domain (East Athabasca Mylonite Triangle of Hanmer, 1997) to the west are found adjacent to significantly lower pressure (ca. 5 kbar) rocks of the Mudjatik Domain (Hearne Province) to the east. Juxtaposition of these two different crustal levels was a result of oblique, west-side-up, dextral-reverse displacement along the moderately west-dipping Black Lake Shear Zone between 1.87 and 1.84 Ga (Mahan and Williams, 2002). Hanmer (1997) suggested that the Tantato Domain represented the northeastern apex of an elliptical

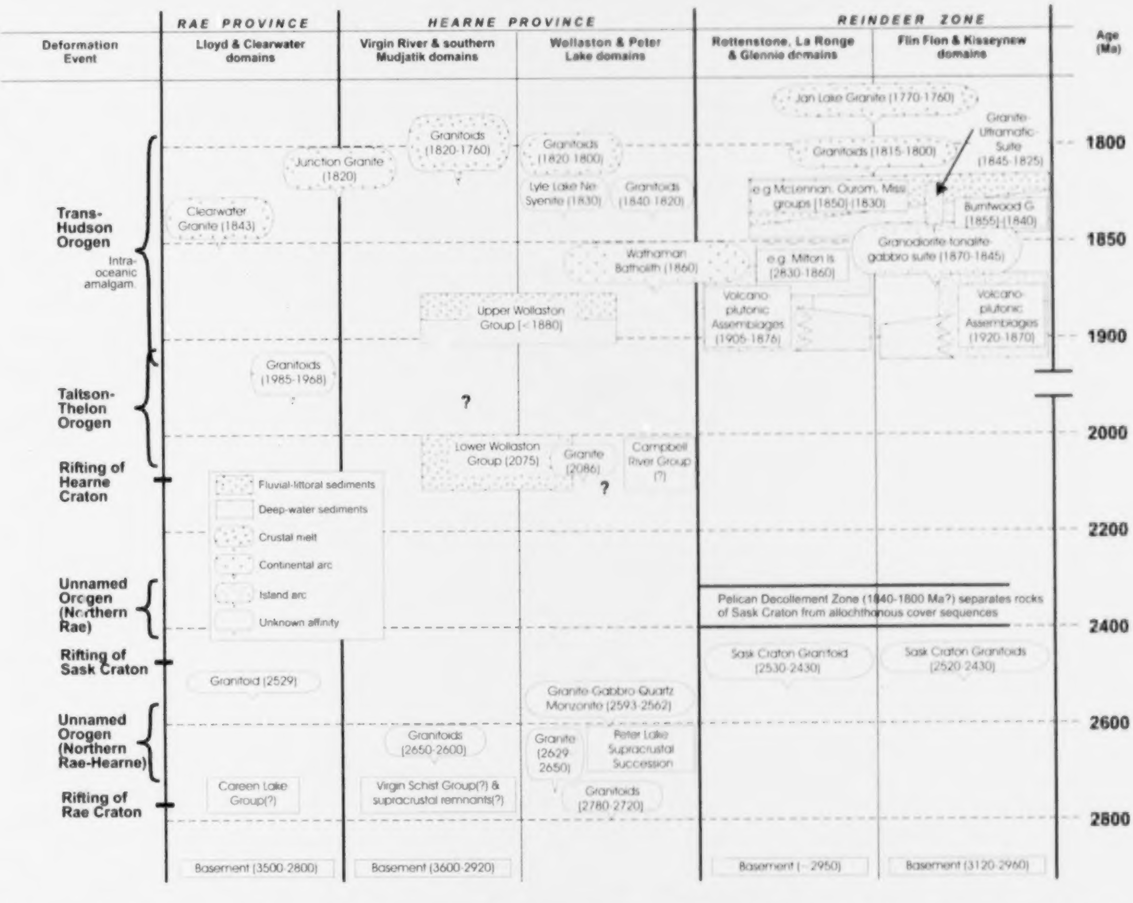

RAE PROVINCE
HEARNE PROVINCE
REINDEER ZONE
Deformation Event
Lloyd & Clearwater domains
Virgin River & southern Mudjatik domains
Wollaston & Peter Lake domains
Rottenstone, La Ronge & Glennie domains
Flin Flon & Kisseynew domains
Age (Ma)
1800
1850
1900
2000
2200
2400
2600
2800
Trans-Hudson Orogen
Intra-oceanic amalgam.
Taltson-Thelon Orogen
Rifting of Hearne Craton
Unnamed Orogen (Northern Rae)
Rifting of Sask Craton
Unnamed Orogen (Northern Rae-Hearne)
Rifting of Rae Craton
Jan Lake Granite (1770-1760)
Granitoids (1820-1760)
Granitoids (1820-1800)
Granitoids (1815-1800)
Granite-Ultramafic-Suite (1845-1825)
Junction Granite (1820)
Lyle Lake Ne Syenite (1830)
Granitoids (1840-1820)
e.g. McLennan, Ourom, Miss groups [1850]-(1830)
Burntwood G. [1855]-(1840)
Clearwater Granite (1843)
Granodiorite-tonalite-gabbro suite (1870-1845)
Wathaman Batholith (1860)
e.g. Milton Is. [2830-1860]
Volcano-plutonic Assemblages (1905-1876)
Volcano-plutonic Assemblages (1920-1870)
Upper Wollaston Group [<1880]
Granitoids (1985-1968)
?
Lower Wollaston Group (2075)
Granite (2086)
?
Campbell River Group (?)
Fluvial-littoral sediments
Deep-water sediments
Crustal melt
Continental arc
Island arc
Unknown affinity
Pelican Decollement Zone (1840-1800 Ma?) separates rocks of Sask Craton from allochthonous cover sequences
Sask Craton Granitoid [2530-2430]
Sask Craton Granitoids [2520-2430]
Granitoid [2529]
Granite-Gabbro-Quartz Monzonite (2593-2562)
Granitoids [2650-2600]
Granite [2629-2650]
Peter Lake Supracrustal Succession
Careen Lake Group(?)
Virgin Schist Group(?) & supracrustal remnants(?)
Granitoids [2780-2720]
Basement (3500-2800)
Basement (3600-2920)
Basement (~2950)
Basement (3120-2960)

***Figure 7** – Lithostructural history of the Rae and southern Hearne provinces, and the Reindeer Zone. Ages in square brackets are based on detrital zircon study; round brackets denote igneous ages. References for age constraints can be found in the text.*

crustal-scale boudin, which continued beneath the Athabasca Basin and re-emerged in the eastern Lloyd Domain (i.e., east of the Clearwater aeromagnetic high). This 'Athabasca lozenge' was thought to be lithologically and isotopically distinct from both the Rae and Hearne wallrocks, and to have been exhumed along the Snowbird Tectonic Zone during Archean time. It is now believed, however, that the rocks of the Tantato Domain are broadly correlative with those of the Beaverlodge Domain across the Grease River Shear Zone. The high-pressure metamorphic character of the Tantato Domain is now known to be ca. 1.9 Ga in age (Baldwin *et al.*, 2000), and appears to drop gradually to the west (Kopf and Williams, 1999). Aeromagnetic trend lines south of the Athabasca Basin show that rocks of the eastern Lloyd Domain (i.e., part of the previously inferred 'lozenge') are continuous to the west and merely overprinted by a younger fabric in the Clearwater Domain (Card, 2001a).

South of the Athabasca Basin, the Snowbird Tectonic Zone is represented by the Virgin River Shear Zone, along which early east-vergent thrusting (Bickford *et al.*, 1994; Card, 2002), constrained to the 1.98 to 1.82 Ga age range, is overprinted by a later dextral reactivation (Carolan and Collerson, 1989). The relative abundance of anorthosite and intermediate to mafic granulites, together with 850 to 930°C peak metamorphic temperatures (Crocker *et al.*, 1993) to the west, is consistent with a model involving uplift of lower crustal material in the Lloyd Domain (Bickford *et al.*, 1994), similar to that along the Black Lake Shear Zone segment of the Snowbird Tectonic Zone in the north. The ca. 1.82 Ga (Bickford *et al.*, 1986) Junction Granite cuts the early mylonitic fabric, but is itself deformed, presumably by the late dextral-shearing event.

Hearne Province

The Hearne Province includes that part of the Shield lying between the Rae Province to the west, where it is bounded by the Snowbird Tectonic Zone (comprising the Virgin River and Black Lake shear zones), and the Reindeer Zone (i.e., the juvenile rocks of the Trans-Hudson Orogen) to the east (Figures 2, 3, 6). The Hearne Province–Reindeer Zone boundary is marked by the Needle Falls and Parker Lake shear zones in the southwest, and the western contact of the intrusive ca. 1.86 to 1.85 Ga Wathaman Batholith in the northeast. The Hearne Province comprises the Virgin River, Mudjatik, Wollaston and Peter Lake domains, which are distinguished largely on the basis of structural style. The Virgin River, Wollaston and Peter Lake domains are essentially northeast-trending straight belts, the former resulting from deformation along the Virgin River Shear Zone and the latter two resulting from shortening associated with the Trans-Hudson Orogen (Figures 6, 8). The centrally located Mudjatik Domain is characterized by arcuate regional structures resulting from late fold interference attributed to the Trans-Hudson Orogen (Table 1). The entire province is underlain by variably reworked Archean basement, which is dominated by foliated to gneissic granitoid rocks (Lewry and Sibbald, 1980; Orrell *et al.*, 1999). Supracrustal rocks of the ca. 2.7 Ga Ennadai Granite-Greenstone Belt, the 2.4 to 1.9 Ga Hurwitz Group and the 2.1 to 1.85 Ga Wollaston Supergroup vary in extent and level of crustal exposure.

Virgin River Domain

The Virgin River Domain is located in the southwestern Hearne Province, between the Virgin River and Cable Bay shear zones (Figure 6). Although exposure is constrained by Athabasca and Phanerozoic cover, aeromagnetic maps show that the domain is continuous, both to the northeast and southwest. Along the western boundary, the **Virgin Schist Group** is dominated by psammopelite, but also includes quartzite, pelite, amphibolite and calc-silicate rocks (Lewry and Sibbald, 1980). Elsewhere, the domain is underlain by granitic orthogneiss with subordinate supracrustal gneisses believed to be derived from the Virgin Schist Group. A steep, eastward-increasing, low- to medium-pressure metamorphic gradient ranges from lower amphibolite facies to the upper amphibolite-granulite facies transition. This thermotectonic event was probably initiated at about 1.93 Ga in response to the Taltson-Thelon Orogen, but was sustained throughout the subsequent Trans-Hudson Orogen, which waned at about 1.80 Ga. The lower amphibolite facies conditions affecting the Virgin Schist Group in the west are probably coeval with the amphibolite facies overprint of granulite facies assemblages in the easternmost Lloyd Domain of the Rae Province (Lewry and Sibbald, 1980).

An early S1 foliation is deformed by upright to steeply inclined, west-northwest-trending F2 folds and subsequent north-northeast-trending F3 folds, the latter being responsible for the main northeast-trending structural fabric. The metamorphic gradient is thought to have existed throughout this interval, but conditions peaked during or shortly after the D3 event (Lewry and Sibbald, 1980). The post-D3, ca. 1.82 Ga (Bickford *et al.*, 1994) Junction Granite crosscuts the main mylonitic fabric in the Virgin River Shear Zone (the Snowbird Tectonic Zone). A subsequent D4 event was responsible for weak shearing of the granite and upright northeast-trending minor folds, which accentuated the northeast-trending structural grain.

Since the Virgin River Domain is lithologically, metamorphically and structurally similar to the Mudjatik Domain to the east, the bounding Cable Bay Shear Zone is thought to result from accommodation during D3 flattened flexural folding (Lewry and Sibbald, 1980).

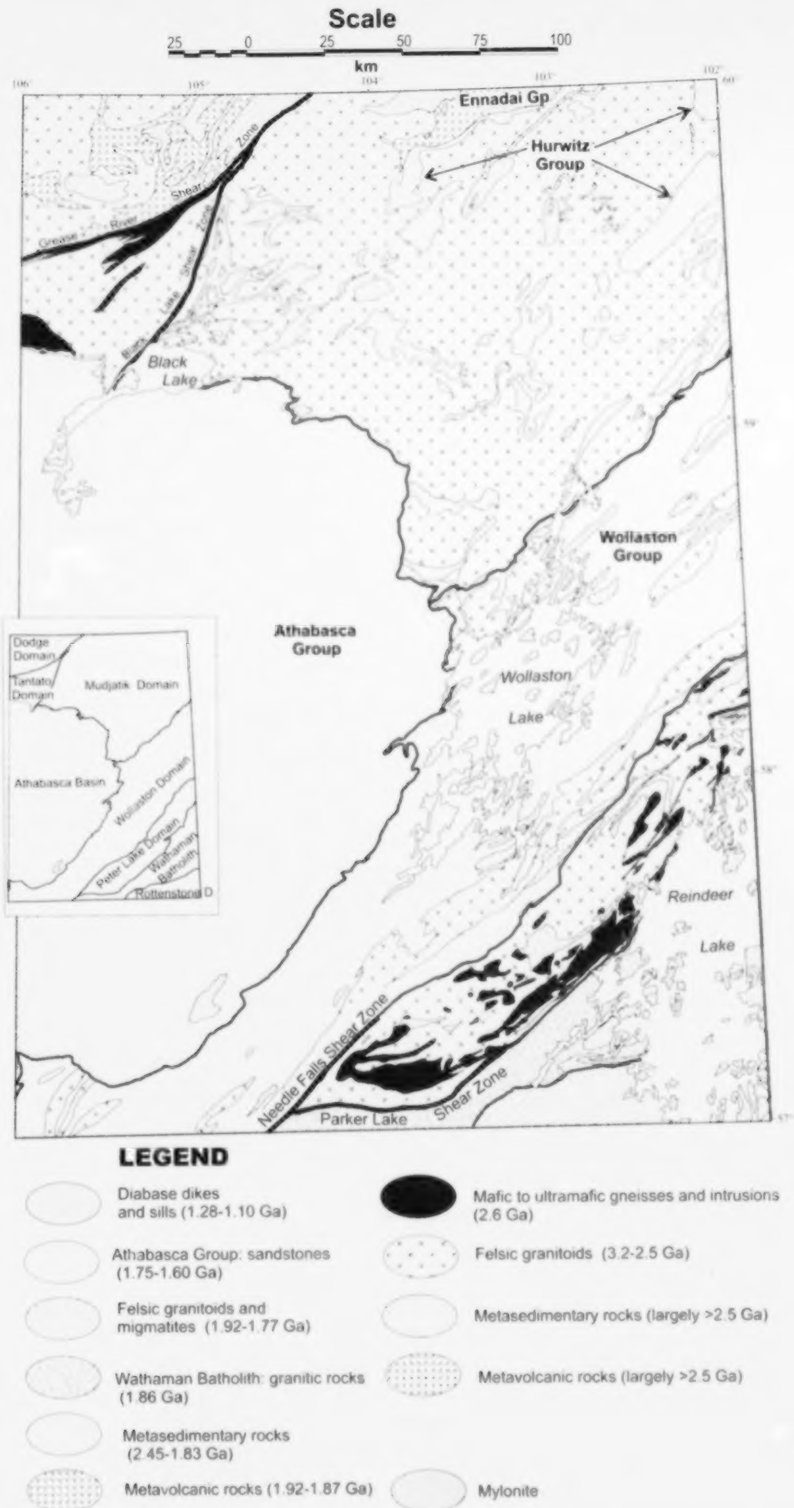

Scale
25
0
25
50
75
100
km
106°
105°
104°
103°
102°
60°
59°
58°
57°
Ennadai Gp
Hurwitz
Group
Grease River Shear Zone
Black Lake Shear Zone
Black
Lake
Wollaston
Group
Athabasca
Group
Wollaston
Lake
Reindeer
Lake
Needle Falls Shear Zone
Parker Lake Shear Zone
Dodge
Domain
Tantato
Domain
Mudjatik Domain
Athabasca Basin
Wollaston Domain
Peter Lake Domain
Wathaman
Batholith
Rottenstone D
LEGEND
Diabase dikes
and sills (1.28-1.10 Ga)
Athabasca Group: sandstones
(1.75-1.60 Ga)
Felsic granitoids and
migmatites (1.92-1.77 Ga)
Wathaman Batholith: granitic rocks
(1.86 Ga)
Metasedimentary rocks
(2.45-1.83 Ga)
Metavolcanic rocks (1.92-1.87 Ga)
Mafic to ultramafic gneisses and intrusions
(2.6 Ga)
Felsic granitoids (3.2-2.5 Ga)
Metasedimentary rocks (largely >2.5 Ga)
Metavolcanic rocks (largely >2.5 Ga)
Mylonite

Figure 8 – Simplified geology of the northern Hearne Province and northern Reindeer Zone.

Table 1 – Comparative deformational chart for the Precambrian of northern Saskatchewan.

Age (Ma)	*RAE PROVINCE*					*HEARNE PROVINCE*					*REINDEER ZONE*			Event
	Northern Rae	Tantato	Carswell	Clearwater	Lloyd	Virgin River	S Mudjatik	N Mudjatik	Wollaston	Peter Lake	Rottenstone	La Ronge	FFGC-KD	
1770				D3 W	D4 WNW	D5 WNW			**D4 NW**	D4 NE open, upright		D4 NE open, upright	**D4 NE** open, upright	
1800	**D5 N** open/upright		D3 N open, steep	**st S dip**	VRSZb-dextral	VRSZb-dextral	**D4 NE** upright	D5 gentle dip	open		D4 N open	D3 N open-close	**D3 N-NW** tight	
1810											**D3 NE**			
1820					**D3 NNE?**	**D4 NNE; meta** upright; CBSZ	**D3 NNE**	D4 NE upright open/tight	**D3 NE** open-tight	D3 ENE close-tight upright	isoclinal **D2 NE** isoclinal	**D2 NE** tight-isoclinal		TH: terminal
1830									**D2** tight-isoclinal				**D2 WNW** tight-iso; PTZ	
1840													**D1 foliation** recumbent	TH: SC-FFG
1850					VRSZa-dextral	VRSZa-dextral								
1860		**LLSZ -dextral** 1870-1840				D3 WNW upright	D2 WNW? upright D1 foliation?	D3 NW open	D1 foliation isoclinal; thrust		D1 foliation	**D1 foliation** D0?	**Pre-D1 amal**	TH: arc amal/ accretion
1900	**D4 NE; meta** tight; st SE BBSZ-dextral	LLSZ-thrust		D2 N? shearing?	**D2 NE** VRSZ-thrust D1 recum	D2 NE VRSZ-thrust D1 recum	recumbent							TT: SI-BH-RC
1985														
2300	**D3 NE; meta** BBSZ thrust		**D2** isoclinal		D0? recumbent	D0? recumbent			D0?					Unnamed orogen
2400	**D2 NW; OBSZ** isocl; myl													
2550	D1 fol; meta		D1 foliation	**D1 foliation**				D2 xenos D1 isocl	D0?	**D2?** D1>2580?				Unnamed orogen?

Note: Timing of events in bold type is geochronologically supported. Question marks indicate approximate age constraints.

Abbreviations: amal, amalgamation of Amisk Collage; fol, foliation; isocl, isoclinal folding; meta, metamorphic event; myl, mylonitization; recum, recumbent folding; SC-FFG, collision between Sask Craton and Flin Flon–Glennie Complex; SI-BH-RC, accretion of Slave Craton and Buffalo Head Terrane to western Rae Craton; st, steep; TH, Trans-Hudson Orogen; TT, Taltson-Thelon Orogen; xenos, defined by foliation in xenoliths.

Shear zones: BBSZ, Black Bay Shear Zone; CBSZ, Cable Bay Shear Zone; LLSZ, Legs Lake Shear Zone; OBSZ, Oldman-Bulyea Shear Zone; PTZ, Pelican Thrust Zone; VRSZ, Virgin River Shear Zone (a and b refer to two periods of dextral displacement).

Mudjatik Domain South of the Athabasca Basin

The Mudjatik Domain of the central Hearne Province is distinguished from the adjacent northeast-trending straight belts by having an arcuate map pattern resulting from regional dome-and-basin fold interference (Figure 6). It is bounded to the west by the Snowbird Tectonic Zone (in the north) and the Cable Bay Shear Zone (in the south), the latter delineating it from the lithologically similar Virgin River Domain. The eastern boundary with the Wollaston Domain is placed somewhat arbitrarily at the transition into dominantly northeast-trending structures. A broadly coincident aeromagnetic low (*see* map in back pocket) is thought to be an artifact of the adjacent aeromagnetic high to the east, owing to the polarized nature of the magnetic data.

The Mudjatik Domain is dominated by variably migmatitic Archean orthogneisses, but also incorporates minor infolded supracrustal outliers of the Wollaston Supergroup in the east, the Ennadai and Hurwitz groups in the north, and an undetermined sequence (Virgin Schist Group?) in the west (Figures 6, 8). South of the Athabasca Basin, T_{DM} model ages from the orthogneiss indicate a crustal history beginning as early as 3.6 Ga, with extensive crust development by about 2.92 Ga (Bickford *et al.*, 1994; Orrell *et al.*, 1999). Uranium-lead zircon dates from rocks in the south and central parts of the domain suggest an Archean thermotectonic event at about 2.78 Ga, followed by widespread granitic plutonism in the 2.65 to 2.6 Ga range (Orrell *et al.*, 1999; Annesley *et al.*, 1999). Pelitic to psammitic supracrustal rocks and mafic granulites, minor quartzites, calc-silicates, marbles and ultramafic rocks, and rare oxide, silicate and sulphide facies iron formation occur in narrow arcuate bands throughout, defining the dome-and-basin pattern. In the east, most of these supracrustal remnants have been correlated with the Wollaston Supergroup (Tran and Smith, 1999); in the west, however, there is a larger component of mafic rocks and the supracrustal succession appears more similar to the undated Virgin Schist Group of the Virgin River Domain, and possibly also to the Ennadai Group of the northern Mudjatik Domain.

Metamorphic conditions peaked in the range of the low- to medium-pressure upper amphibolite to granulite facies transition, with one P-T study in the west indicating temperatures of 750 ± 50°C at pressures of about 5.5 kbar (Orrell *et al.*, 1999). Metamorphic reworking in the west, between 2.1 and 1.9 Ga (Bickford *et al.*, 1994; Orrell *et al.*, 1999), is probably correlative with coeval thermotectonic events in the Rae Province, where they are tentatively attributed to terrane accretion at the western margin of the Rae Craton. A much more regional and intense reworking of the entire Hearne Craton took place at 1.82 to 1.80 Ga due to deformation associated with the Trans-Hudson Orogen to the east (Bickford *et al.*, 1994; Orrell *et al.*, 1999; Annesley *et al.*, 1999).

The three regional deformational events are thought to be correlative with the first three events in the Virgin River Domain (Lewry and Sibbald, 1980). The first resulted in a flat-lying regional foliation due to recumbent F1 folding. This was overprinted by roughly orthogonal sets of upright, flattened flexural folds to produce a dome-and-basin interference pattern. The F2 folds are upright, west-northwest to north-northwest oriented, and accompanied by a collinear rodding and mineral-aggregate lineation. They were followed by upright, northeast- to east-northeast-trending F3 folds. Lewry and Sibbald (1980) originally attributed this deformational style to the upward transport of migmatite lobes, although Tran (2001) has suggested an alternative origin resulting from multiple shortening events, based on work in the Wollaston Domain and along the Mudjatik-Wollaston boundary.

Lewry and Sibbald (1980) maintained that at least upper amphibolite facies conditions persisted from D1 through to D3 time, after which static recrystallization resulted in the assemblages seen today. Weakly deformed to augen granites and pegmatites, emplaced between ca. 1.82 and 1.76 Ga (Orrell *et al.*, 1999), indicate that at least the northeast-trending D3 event was produced during the Trans-Hudson Orogen.

Mudjatik Domain North of the Athabasca Basin

North of the Athabasca Basin, the Mudjatik Domain is also dominated by Archean granitic gneisses and migmatites. In addition, it includes a southeastern extension of the 700 km long Archean Ennadai-Rankin Greenstone Belt, the Paleoproterozoic Hurwitz Group and a variety of Paleoproterozoic intrusions (Figure 8). The Archean orthogneisses and migmatites are thought to include ca. 3.3 to 2.8 Ga cratonic remnants (Hanmer, 1997; Aspler and Chiarenzelli, 1996), represented by granitic and tonalitic migmatites as well as mylonitic granites and amphibolites at the eastern margin of the Snowbird Tectonic Zone (Harper *et al.*, 2001). Elsewhere, these granitic gneisses and migmatites are considered broadly correlative with voluminous ca. 2.7 to 2.6 Ga granitoid intrusions (Peterson and Lee, 1995; Peterson *et al.*, 2000) and ca. 2.55 to 2.5 Ga granites derived during a period of regional thermotectonism in the Nunavut segment of the Hearne Province (Davis *et al.*, 2000b).

The **Ennadai-Rankin Greenstone Belt** comprises mafic flows and tuffs, subordinate intermediate and felsic volcanic rocks, and mafic to ultramafic intrusive equivalents. Psammopelitic to pelitic schists and iron formation are interlayered with the volcanic rocks (Reilly, 1993b; Harper *et al.*, 2001; Coulson *et al.*, 2001). In the main part of the belt, deformation is relatively weak and metamorphism ranges from upper greenschist to lower amphibolite facies; however, these rocks can be traced into more strongly deformed, upper amphibolite to granulite facies equivalents toward the southwest and in outlying belts of similar rocks, which have also been correlated with the Ennadai Group (Harper *et al.*, 2001, 2002). Uranium-lead zircon ages of 2682 ± 6 Ma (Chiarenzelli and Macdonald, 1986) from a felsic volcanic rock and 2708 +3/-2 Ma from a granodiorite that intrudes mafic metavolcanic rocks (Delaney *et al.*, 1990; Reilly, 1993b) are consistent with ages determined along strike in Nunavut (Mortenson and Thorpe, 1987; Patterson and Heaman, 1990; Cavell *et al.*, 1992; Davis and Peterson, 1998). A titanite age from the granodiorite also yielded a minimum age of 1771 ± 14 Ma (Heaman, pers. comm. *quoted in* Reilly, 1993b), indicating a Hudsonian overprint attributable to the Trans-Hudson Orogen. Volcanic and sedimentary supracrustal remnants south of the Athabasca Basin are similar to the Ennadai Group, suggesting possible southwestward extension for another 450 km.

The Paleoproterozoic **Hurwitz Group**, which outcrops discontinuously along the Manitoba boundary in the far northeast (Figure 8), comprises basal pelitic-psammopelitic schist and overlying dolomitic marble containing local calc-silicate layers (Munday, 1973b; Reilly, 1993a), and an upper psammopelitic-psammitic sequence (Harper *et al.*, 2002). Munday (1973b) originally referred to these sedimentary rocks as the Many Islands Group, but had considered them equivalent to the Hurwitz Group. Farther west, the Hurwitz Group consists of pelite, calcareous pelite, calc-silicate, marble, psammopelite, and minor quartzite and volcanic rock. It outcrops along the southeastern margin of the Ennadai-Rankin Greenstone Belt, which it structurally underlies. Progressively more deformed, upper amphibolite to granulite facies rocks of the Hurwitz Group have been traced southwestward for at least 70 km.

Correlation of the Hurwitz Group in Saskatchewan with the type locality in Nunavut is currently based on lithological similarities. A sequence of pelite, calcareous pelite, quartzite and minor calc-silicate rock in the western Mudjatik Domain is considered part of the Ameto Formation of the lower Hurwitz Group as defined in Nunavut (Harper *et al.*, 2001), where they are intruded by 2.11 Ga gabbro sills (Heaman and LeCheminant, 1993). Marble and calc-silicate rock are correlated (Reilly, 1993b; Harper *et al.*, 2001) with the Watterson Formation, and psammopelite and quartzite with the Ducker Formation, both of which are parts of the upper Hurwitz Group in Nunavut (Aspler *et al.*, 1992). Detrital zircon studies of the upper Hurwitz Group indicate deposition after ca. 1.96 Ga (Davis *et al.*, 2000a). Locally along the eastern margin of the Ennadai-Rankin Greenstone Belt, thrust slices of the Ennadai Group are interleaved with the Hurwitz Group. Hurwitz Group rocks are intruded by, and occur as xenoliths in, late- to post-tectonic Paleoproterozoic leucotonalites and leucogranites, which probably include both the 1.85 to 1.81 Ga Hudson granites and the ca. 1.76 Ga fluorite-bearing Nueltin granites that extend in northeast-trending belts through much of Nunavut (Peterson *et al.*, 2000). Deposition of the upper Hurwitz Group overlaps temporally with that of the Wollaston Supergroup, possibly demonstrating a genetic link between the two sediment-dominated sequences.

The structural style in the northern Mudjatik Domain varies from a broad straight belt in the Ennadai-Rankin Greenstone Belt to the more characteristic, and likely overprinting, dome-and-basin fold interference pattern of the more highly metamorphosed rocks. Pre-Hurwitz deformation includes development of D1 isoclinal folding, together with an axial-planar regional foliation, and is overprinted by a second, crosscutting D2 foliation, which is axial planar to folds defined by inclusions within the migmatites (Harper *et al.*, 2001). An associated Archean high-grade metamorphic event is indicated by the presence of abundant leucosome in tonalitic and granitic migmatites of the basement. Archean metamorphism of the Ennadai Group probably ranged from greenschist to upper amphibolite facies.

Post-Hurwitz Group (i.e., post-1.96 Ga) D3 deformation resulted in open, northwest-trending folds, northeast-plunging 'a' lineations and southwest-verging thrust faults, resulting in a thrust stack in which the Ennadai Group structurally overlies and is interleaved with the Hurwitz Group. Upright to steeply inclined, open to tight, northeast-trending D4 folds interact with D3 folding to create a dome-and-basin fold-interference pattern. This deformational history is strikingly similar to that south of the Athabasca Basin and helps to constrain the age of the D3-D4 deformation to <1.96 Ga throughout the Mudjatik Domain. Associated Paleoproterozoic metamorphism ranged from lower amphibolite to granulite facies, as indicated by diagnostic mineral assemblages in Hurwitz Group metasedimentary rocks.

The eastern domain boundary is taken at the lithological transition from dominantly magnetiferous granitoid gneisses of the Mudjatik Domain to dominantly magnetite-poor Wollaston Supergroup paragneisses of the Wollaston Domain, since the rocks on both sides exhibit the same linear structural trend in this part of the Hearne Province.

Wollaston Domain

The Wollaston Domain (Figures 6, 8) is a northeast-trending, tightly folded belt of Archean granitoids and Paleoproterozoic metasedimentary rocks (e.g., Money, 1968; Money *et al*, 1970; Ray, 1979b; Lewry and Sibbald, 1979, 1980; Ray and Wanless, 1980; Lewry, 1981b; Stauffer, 1984). The metasedimentary rocks are collectively termed the '**Wollaston Supergroup**' and are interpreted as remnants of a rift–passive margin–foreland basin succession deposited along the eastern margin of the Hearne Craton (Figure 9).

From the Shield margin to Pardoe Lake, the Needle Falls Shear Zone, a late Paleoproterozoic dextral fault system (Munday, 1974; Ray, 1974; Stauffer and Lewry, 1988), separates the Wollaston Domain from the 1.86 to 1.85 Ga Wathaman Batholith and juvenile terranes of the Reindeer Zone to the east. Farther north, supracrustal rocks of the Wollaston Domain rest unconformably on Archean gneisses of the Peter Lake Domain (MacNeil *et al.*, 1997). The western contact with the Mudjatik Domain is marked by a transition in structural style from a linear belt to one characterized by dome-and-basin fold interference. An increase in the proportion of Archean granitoid basement roughly coincides with this structural transition (Lewry and Sibbald, 1980), but no tectonic break is apparent (Tran *et al.*, 1999; Tran and Smith, 1999).

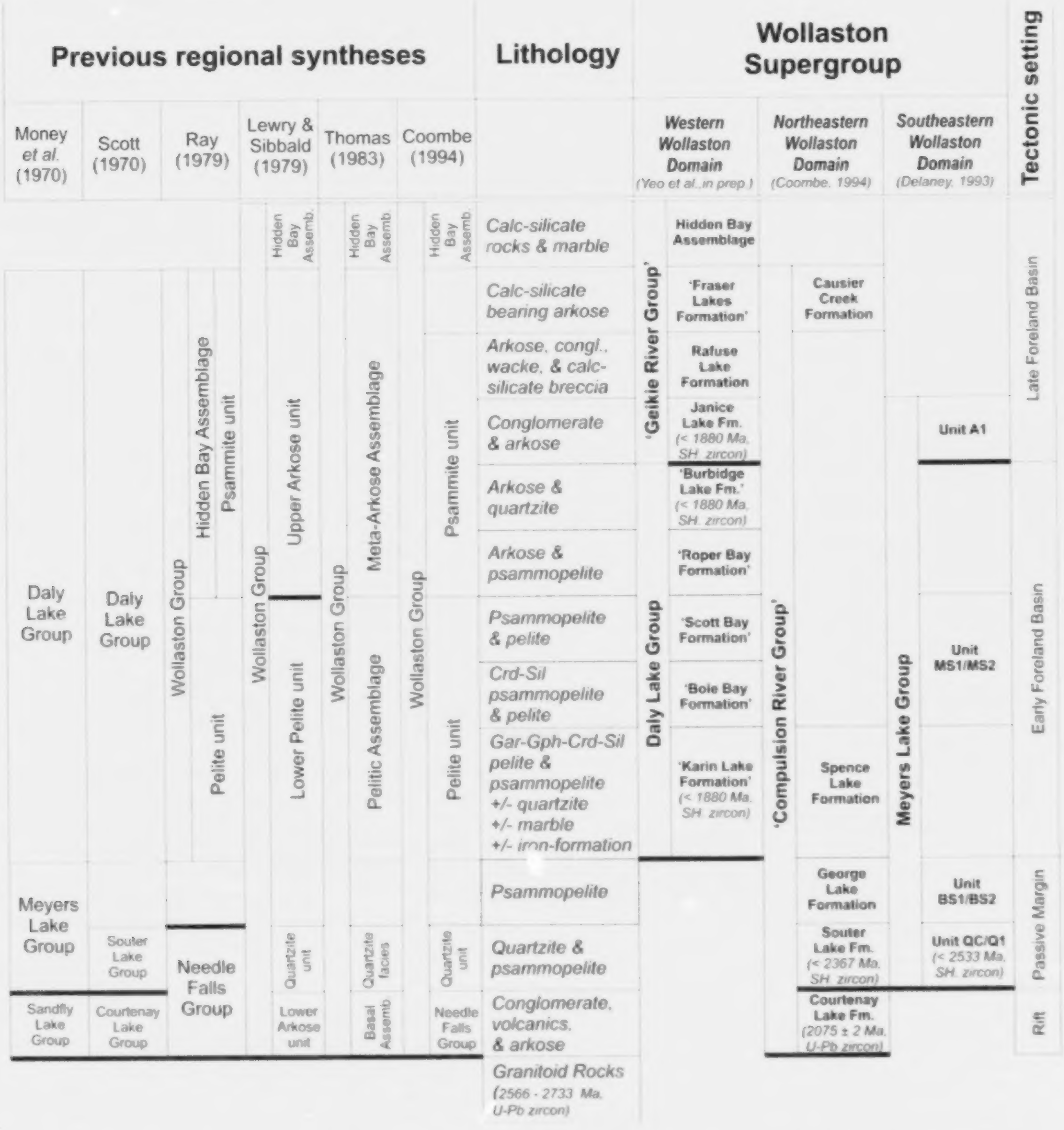

Previous regional syntheses
Lithology
Wollaston Supergroup
Tectonic setting
Money et al. (1970)
Scott (1970)
Ray (1979)
Lewry & Sibbald (1979)
Thomas (1983)
Coombe (1994)
Western Wollaston Domain (Yeo et al., in prep.)
Northeastern Wollaston Domain (Coombe, 1994)
Southeastern Wollaston Domain (Delaney, 1993)
Hidden Bay Assemb.
Hidden Bay Assemb.
Hidden Bay Assemb.
Calc-silicate rocks & marble
Calc-silicate bearing arkose
Arkose, congl., wacke, & calc-silicate breccia
Conglomerate & arkose
Arkose & quartzite
Arkose & psammopelite
Psammopelite & pelite
Crd-Sil psammopelite & pelite
Gar-Gph-Crd-Sil pelite & psammopelite +/- quartzite +/- marble +/- iron-formation
Psammopelite
Quartzite & psammopelite
Conglomerate, volcanics, & arkose
Granitoid Rocks (2566 - 2733 Ma, U-Pb zircon)
Daly Lake Group
Daly Lake Group
Meyers Lake Group
Souter Lake Group
Sandfly Lake Group
Courtenay Lake Group
Wollaston Group
Hidden Bay Assemblage
Psammite unit
Pelite unit
Needle Falls Group
Wollaston Group
Upper Arkose unit
Lower Pelite unit
Quartzite unit
Lower Arkose unit
Wollaston Group
Meta-Arkose Assemblage
Pelitic Assemblage
Quartzite facies
Basal Assemb.
Wollaston Group
Psammite unit
Pelite unit
Quartzite unit
Needle Falls Group
'Geikie River Group'
Daly Lake Group
Hidden Bay Assemblage
'Fraser Lakes Formation'
Rafuse Lake Formation
Janice Lake Fm. (< 1880 Ma, SH zircon)
'Burbidge Lake Fm.' (< 1880 Ma, SH zircon)
'Roper Bay Formation'
'Scott Bay Formation'
'Bole Bay Formation'
'Karin Lake Formation' (< 1880 Ma, SH zircon)
'Compulsion River Group'
Causier Creek Formation
Spence Lake Formation
George Lake Formation
Souter Lake Fm. (< 2367 Ma, SH zircon)
Courtenay Lake Fm. (2075 ± 2 Ma, U-Pb zircon)
Meyers Lake Group
Unit A1
Unit MS1/MS2
Unit BS1/BS2
Unit QC/Q1 (< 2533 Ma, SH zircon)
Late Foreland Basin
Early Foreland Basin
Passive Margin
Rift

Figure 9 – Stratigraphic relationships within the Wollaston Supergroup. Dark lines indicate inferred unconformities. All radiometric ages are for detrital zircons, except for basement ages and the Courtenay Lake porphyry, which are sensitive high-resolution ion microprobe (SHRIMP) ages. Abbreviations: Assemb., Assemblage; congl., conglomerate; Crd, cordierite; Gph, graphite; Gar, garnet; SH, SHRIMP age; Sil, sillimanite.

The Archean basement is dominated by relatively homogeneous, foliated granitic to tonalitic rocks, yielding 2.78 to 2.72 Ga and 2.65 to 2.57 Ga U-Pb zircon ages (Krogh and Clark, 1987; Annesley *et al.*, 1992, 1999 and pers. comm., 2001; Hamilton *et al.*, 2000; Bickford *et al.*, 2002), but also includes minor mafic bodies. The ca. 2.75 Ga rocks are broadly coeval with the ca. 2.7 Ga Ennadai Group of the northern Mudjatik Domain, whereas the ca. 2.6 Ga granites are considered part of a widespread suite found throughout much of the northern Rae and Hearne provinces (e.g., Davis *et al.*, 2000b). A 2.57 Ga metamorphic overprint identified in one sample (Annesley *et al.*, 1992) is also consistent with the thermotectonic history of the northern Hearne Province (Davis *et al.*, 2000), whereas rare ca. 2.3 Ga ages (Bickford *et al.*, 1988; Annesley *et al.*, pers. comm., 2001) suggest that the regional thermotectonic event of that age affecting much of the Rae Province may also have extended into the Hearne Province.

Development of a consistent stratigraphic sequence for the Wollaston Supergroup is difficult due to the high metamorphic grade and complex deformation; however, recent mapping shows that a number of regionally extensive formations can be distinguished (Figure 9). Supracrustal rocks in the Wollaston Domain can be broadly divided into two contrasting successions: 1) conglomerate, feldspathic arenite and ca. 2.075 Ga bimodal volcanic rocks (Delany *et al.*, 1997) of the 'Compulsion River Group', which is interpreted as a rift succession and overlying passive-margin strata (Coombe, 1994; Fossenier *et al.*, 1995); and 2) a younger succession of quartzite, psammopelite, pelite and calc-silicate–bearing feldspathic arenite belonging to the 'Daly Lake' and 'Geikie River' subgroups. These younger strata were originally interpreted to be a passive-margin succession (Coombe, 1994; Delaney *et al.*, 1997); however, based on Trans-Hudson–age detrital zircons as young as 1.88 Ga, found in all but the lowermost units, it is now thought to a foreland basin (Figure 9; Tran, 2001).

The inferred foreland-basin fill is widespread over most of the Wollaston Domain. The lower strata, which constitute the Daly Lake Group, broadly coarsen upward from pelites, through psammopelites, to meta-arkoses. Marble, restricted to the craton side of the domain, with ferruginous strata more common to the east, suggest starved basin conditions during the early phase of foreland-basin development. An extensive conglomerate at the base of the overlying Geikie River Group marks a widespread unconformity, which may reflect a collision along the southeast margin of the Hearne Province. The conglomerate interfingers with, and is overlain by, arkose, calc-silicate-bearing arkose and psammopelite. Quartzite, calc-silicate rock and marble of the Hidden Bay Assemblage (Wallis, 1971) in the Wollaston Lake area, farther to the north, may be correlative with Geikie River Group strata.

Evidence of Archean deformation is limited to foliated basement clasts in Wollaston conglomerates. Four phases of Paleoproterozoic ductile deformation affect the Wollaston Supergroup (e.g., Tran *et al.*, 1999; Tran and Smith, 1999). The first was responsible for the main regional fabric, which is partially defined by melt leucosome, along with rare isoclinal folds and development of a décollement along the basement-cover contact. This was followed by tight to isoclinal D2 folds, which are in turn overprinted by open to tight, northeast-trending D3 folds. The latter, which control the structural grain, are doubly plunging with steeply southeast-dipping axial planes, and produce type 3 fold-interference patterns where they overprint D1 or D2 folds. Axial-planar melt leucosome indicates a second period of metamorphic mineral growth, which is thought to have taken place under peak conditions. Steep to vertical, northeast-trending, oblique reverse shears truncate D3 folds but predate open, upright, northwest-trending D4 folds, which locally produce type 1 fold interference and may be partly responsible for the domal basement structures. Late, sinistral, north- to northwest-trending brittle faults may be part of the Tabbernor Fault.

The metamorphic grade within the Wollaston Domain exhibits a steep, westward-increasing gradient from upper greenschist to lower amphibolite facies, along parts of the eastern margin, to upper amphibolite and lower granulite facies farther west (Lewry *et al.*, 1978; Lewry and Sibbald, 1980). Two main, high-temperature, low-pressure thermotectonic events are distinguished, the second of which attained peak conditions (ca. 770°C at 5 kbar) and was associated with D3 deformation (Tran and Yeo, 1997; Tran *et al.*, 1998; Tran *et al.*, 1999; Yeo and Savage, 1999). Since the metamorphic grade exhibited by the basement granitoid rocks is indistinguishable from that of the Wollaston Supergroup, both of the observed thermotectonic events are considered Paleoproterozoic and attributed to the Trans-Hudson Orogen. Geochronological studies reveal two age groupings related to the Trans-Hudson Orogen overprint: 1) a 1.84 to 1.82 Ga suite of granites and gabbroic rocks, which may include crustal melts related to early accretion of the La Ronge arc complex to the eastern Hearne Craton margin, as well as late successor plutons related to subsequent subduction; and 2) 1.82 to 1.80 Ga anatectic granites, pegmatites and metamorphic mineral growth (titanite cooling ages extend to 1.78 Ga), reflecting terminal collision (Annesley *et al.*, 1992, 1999 and pers. comm., 2001).

Peter Lake Domain

The unusual character of the Peter Lake Domain, compared to other areas of the Hearne Province, warrants separate domain status and description. It is located along the southeastern edge of the Hearne Province, wedged between the Wollaston Domain to the northwest and the Paleoproterozoic Wathaman Batholith to the southeast (Figure 9). In the southwest, it is bounded by the Needle Falls Shear Zone (Money, 1965; Stauffer and Lewry, 1993) along the northwest margin, and the Parker Lake Shear Zone (Ray, 1975; Lafrance and Varga, 1996) along the southeast margin. In the northeast, the domain is unconformably overlain by rift-related rocks of the Courtenay-Cairns belt and younger Wollaston Supergroup sedimentary rocks along its northwestern margin (Ansdell *et al*., 2000). The 1.86 to 1.85 Ga Wathaman Batholith, an inferred continental arc related to the Trans-Hudson Orogen, intrudes the domain along its southeastern margin (Corrigan *et al*., 2000).

The Peter Lake Domain is considered largely Archean, but has been intruded by Paleoproterozoic granitoids attributed to the Trans-Hudson Orogen. Felsic to intermediate orthogneisses of the Peter Lake Complex yielded ages of 2.64 to 2.56 Ga (Bickford *et al*., 1992; Annesley *et al*., 1992; Rayner *et al*., 2001; Bickford *et al*., 2002), which correspond very well to the latter of two Archean granitoid-emplacement ages determined elsewhere in the Hearne Province (Figure 7). Mafic to ultramafic intrusive rocks are particularly common in the southeast, where the Swan River Complex has yielded a 2.56 Ga U-Pb zircon age (Corrigan *et al*., 2001). A ca. 2.53 Ga metamorphic event, suggested by rare titanite ages (Annesley *et al*., 1992; Maxeiner and Hunter, 2002) and by SHRIMP rim analyses (Bickford *et al*., 2002), is considered broadly correlative with the regional 2.55 to 2.50 Ga thermotectonic event recognized in the Nunavut segment of the Hearne Craton (Davis *et al*., 2000). The Parker Lake Gneisses are high-strain equivalents of the Peter Lake and Swan River complexes that have yielded U-Pb zircon ages of 2.63 and 2.566 Ga for granitic and granodioritic gneisses, respectively (Bickford *et al*., 2002).

Partly migmatized supracrustal gneisses, including psammopelite, pelite, minor ferruginous sedimentary rocks, and mafic to felsic volcanic rocks are intruded by a gabbroic suite (Maxeiner and Hunter, 2002) that is in turn cut by 2.566 Ga granitic rocks (Annesley *et al*., 1992), confirming their Archean age. In contrast, the low-grade Campbell River Group (Lewry, 1977a; MacDougall, 1987) occupies narrow belts within the southeastern part of the domain, and comprises slate, phyllite, psammite, and minor chert and mafic metavolcanic rocks. Although originally considered Archean (Macdonald and Thomas, 1983), it may be broadly correlative with the Paleoproterozoic Wollaston Supergroup to the west.

A variety of Paleoproterozoic granitoid rocks, some of them fluorite bearing, intrude the Archean infrastructure. The Feaviour Peninsula granite and granitic gneiss at Reindeer Lake both yielded U-Pb zircon ages of 1.86 Ga (Corrigan *et al*., 2001), and are correlated with the Wathaman Batholith. Alkaline intrusive rocks, including the ca. 1.83 Ga (Lloyd Clark, pers. comm. *quoted in* Quirt, 1992) Lyle Lake nepheline syenite (Quirt, 1992, 1993), are also relatively common. East-striking lamprophyre dikes intruding the Campbell River Group (MacDougall, 1987) are of unknown age, but together these alkaline rocks have much in common with lamprophyre-syenite suites in the Uranium City and Baker Lake areas, where they are considered products of the Trans-Hudson Orogen.

Early D1 deformation was likely Neoarchean in age, based on a number of observations, including the presence of deformed mafic volcanic xenoliths in gabbroic rocks possibly related to the Swan River Complex (Maxeiner and Hunter, 2002). The main regional foliation, which affects the majority of units in the Peter Lake Domain, was formed during a second (D2) deformational event and resulted in the development of a mineral foliation and gneissic fabric. At least one upper amphibolite facies metamorphic event, likely coinciding with D2, has affected large parts of the Peter Lake Domain, as well as sedimentary rocks along its northwestern margin (MacNeil *et al*., 1997). Most of the mafic intrusive rocks and the migmatitic supracrustal rocks between Peter Lake and Warner Lake were affected by this high-grade event, but the Campbell River Group was not exposed to this upper amphibolite facies metamorphic event. A third regional deformation event (D3) is manifested in east-northeast-trending, upright, close to tight folds and associated lower amphibolite facies mineral assemblages. The Needle Falls and Parker Lake shear zones likely formed during this D3 event, which postdated deposition of the 2.01 to 1.9 Ga Wollaston Supergroup and emplacement of the 1.86 Ga Wathaman Batholith. Gentle map-scale open warping and decimetre- to metre-scale open folding are related to northeast-trending D4 folds. Late, north-trending, subvertical brittle faults belonging to the Tabbernor Fault system are likely coeval with this D4 folding event.

Synthesis of the Hearne Province

The Hearne Province is composed primarily of Archean granitoid rocks. There is some evidence in the Mudjatik Domain of an early 3.3 to 2.8 Ga history, and crust in both the Mudjatik and Hearne domains had been stabilized by 2.78 to 2.72 Ga. The 2.71 to 2.68 Ga Ennadai-Rankin Greenstone Belt extends into the northern Mudjatik Domain from Nunavut. Undated supracrustal remnants in the southern Mudjatik Domain and granite-greenstone rocks of similar age in the Dodge Domain of the northeastern Rae Province may be correlative. A 2.65 to 2.56 Ga granitic plutonic suite found throughout the Hearne Province was closely followed by a poorly documented thermotectonic event at 2.57 to 2.53 Ga. Subsequent, weak metamorphic events in the west, at 2.3, 2.1 and 1.9 Ga, apparently correlate with stronger, coeval thermotectonic events in the Rae Province, which are thought to record terrane accretion at the western margin of the Rae Craton. The first phase of post-Hurwitz (i.e., 2.1 to 1.9 Ga) deformation resulted in northwest-trending structures in the west and north. These were overprinted by the dominant northeast-trending structures of the Virgin River and Mudjatik domains, which are attributed to ca. 1.9 Ga deformation along the Snowbird Tectonic Zone.

Rifting of the Hearne Craton ca. 2.075 Ga opened the Manikewan Ocean (Stauffer, 1984) and led to deposition of the lowermost Wollaston Supergroup in rift and passive-margin settings. Closure of this ocean during the Trans-Hudson Orogen is documented by 1) deposition of the Hurwitz and main Wollaston groups in inferred foreland-basin settings; 2) intrusion of the east-flanking 1.86 to 1.85 Ga Wathaman Batholith and a variety of 1.84 to 1.82 Ga granitic, syenitic and gabbroic intrusions; and 3) widespread 1.82 to 1.80 Ga metamorphism. Shortening associated with terrane accretion and terminal collision is recorded by four phases of post-Wollaston deformation in the east, which included development of a basal décollement along the basement-Wollaston contact. The intensity of D3 structures led to the northeast-trending structural fabric in the Wollaston and Peter Lake domains, whereas the smaller amplitude of these D3 structures in the Mudjatik Domain, together with orthogonal D2 folding, led to a basin-and-dome interference pattern. It is noteworthy that, in spite of their coplanar orientation, the dominant northeast-trending structural fabric in the Virgin River Domain to the west and the Wollaston and Peter Lake domains to the east is probably diachronous.

As originally defined by Lewry and Sibbald (1977), the boundaries between the Mudjatik Domain and the flanking Virgin River and Wollaston domains were based on changes in structural style from arcuate to more linear structures. The former contact coincides with the intracontinental Cable Bay Shear Zone but, in spite of suggestions to the contrary (Annesley and Madore, 1988, 1989; Hoffman, 1990), recent work has failed to identify a fundamental break along the Mudjatik-Wollaston boundary (Tran *et al.*, 1998, 1999; Tran and Smith, 1999; Yeo and Savage, 1999). A roughly collinear aeromagnetic low, which broadly overlaps the Mudjatik-Wollaston domain boundary, is now viewed as an artifact of the adjoining aeromagnetic high defined by magnetiferous basement granitoids and psammitic paragneisses in the Wollaston Domain.

Needle Falls and Parker Lake Shear Zones

The Needle Falls Shear Zone is a northeast-trending, ductile, high-strain zone that generally marks the eastern boundary of the southern Wollaston Domain (Figures 6, 8). At the boundary between the Wollaston, Wathaman and Peter Lake domains, the Needle Falls Shear Zone bifurcates, with one arm continuing along strike northeastward to die out within a short distance on the northwest side of the Peter Lake Domain. The other arm, termed the 'Parker Lake Shear Zone', follows the southern boundary of the Peter Lake Domain. Where the Peter Lake Domain boundary turns north-eastward, the Parker Lake Shear Zone bifurcates, with the main branch following the domain boundary, and the other, termed the 'Reilly Lake Shear Zone', maintaining an eastward orientation across the Wathaman Batholith.

The main Needle Falls Shear Zone is generally subvertical, up to 1 km in width and comprises protomylonitic to ultramylonitic gneisses. A variety of kinematic indicators infer a dextral sense of displacement, which has been estimated at a minimum of 50 km (Stauffer and Lewry, 1993). The Parker Lake and Reilly Lake splays also exhibit a dextral sense of shear. Although the Needle Falls–Parker Lake segments generally mark the boundary between Archean rocks of the Hearne Craton and Paleoproterozoic juvenile rocks of the Reindeer Zone, it is not considered a suture, since the adjacent Wathaman Batholith is viewed as a continental magmatic arc (e.g., Lewry and Sibbald, 1980). Archean rocks thought to be inliers of the Hearne Craton have also been identified in the Rottenstone Domain to the east (Bickford and Hill, 2000). Rather, the shear zone is considered either a late-tectonic oblique collisional structure or a product of counter-clockwise oroclinal rotation of the southern part of the orogen (Stauffer and Lewry, 1993).

Sub–Athabasca Group Basement

The sub–Athabasca Group basement was originally studied by Gilboy (e.g., 1985). Much of the available drillcore and geophysical information is limited to a perimeter zone 15 to 30 km wide; however, new uranium exploration constantly adds to this database. The aeromagnetic trace of the Snowbird Tectonic Zone effectively divides the sub-Athabasca basement into Rae and Hearne components (Figure 5). The former has distinctive, alternating, high and low, linear magnetic signatures that can be traced north from the Lloyd Domain and south from the Tantato Domain toward the axis of the basin. Areas of alternating high and low magnetic signature likely correspond to areas of mafic granulite facies rocks and/or granitoid gneiss and paragneiss, respectively, which outcrop north and south of the basin. Granitic rocks equivalent to the Clearwater and Junction granites are not conspicuous in drillcore.

The Hearne segment, in the east, is characterized by extensive domal structures cored by Archean granitoid basement and overlain by Wollaston Supergroup graphitic pelite and feldspathic psammite. The linear aeromagnetic high that typifies the Wollaston Domain can be traced along strike under the eastern extremity of the basin. A 20 to 30 km wide, negative aeromagnetic anomaly near the Wollaston-Mudjatik domain boundary also extends under the basin. Although many of the unconformity-type uranium deposits appear to be situated along this trend, it is not viewed as a major tectonic discontinuity. Rather, it may be a geophysical artifact of the exceptionally high, positive aeromagnetic anomaly defined by northeast-trending Archean basement granitoid gneiss and Wollaston Supergroup psammitic paragneiss to the southeast. The arcuate magnetic signature of the southern Mudjatik Domain and the conspicuous magnetic high associated with the Virgin River Domain both continue northward under the Athabasca Basin.

Sask Province

The Sask Province consists of the largely buried Archean Sask Craton, the extent of which can be estimated from regional aeromagnetic maps (*see* aeromagnetic map in back pocket). It is exposed in small tectonic windows within the western Glennie and western Flin Flon domains of the southern Reindeer Zone (Figure 10), but a combination of Nd isotopic studies and LITHOPROBE seismic profiles (e.g., Lewry *et al.*, 1994; Lucas *et al.*, 1994; Prokopiuk and Ansdell, 2000) show that it underlies virtually the entire Reindeer Zone in Saskatchewan, pinching out at depth beneath the Rottenstone Domain.

On the exposed Shield, kinematic indicators show that the Sask Craton has been tectonically overridden by the Flin Flon–Glennie Complex along a several kilometre thick, southwest-verging mylonite zone. Their collision at about 1.84 Ga is thought to have been responsible for the dominant west-northwesterly structural trend in the Paleoproterozoic cover rocks of the eastern Reindeer Zone. The structural domes in which the Sask Craton is exposed are attributed to subsequent fold interference resulting from collision of the Superior Craton.

The Nistowiak Lake, Iskwatikan Lake and Hunter Bay tectonic windows in the Glennie Domain (Figure 10) are dominated by 2.53 to 2.43 Ga calc-alkaline orthogneisses and plutonic rocks, but include inherited ca. 2.95 Ga zircons, 2.72 Ga zircon cores and a 2.71 Ga T_{DM} model age, all of which indicate an older history (Chiarenzelli *et al.*, 1998; Rayner *et al.*, pers. comm., 2001; Bickford *et al.*, 2002). In the Pelican Window of the Flin Flon Domain, upper amphibolite to granulite facies pelitic migmatites and 3.12 to 2.96 Ga quartzofeldspathic gneisses of dominantly igneous parentage are intruded by a 2.49 to 2.43 Ga tholeiitic suite ranging from norite to charnockite (e.g., Sahli Granite; Ashton *et al.*, 1999b; Bickford *et al.*, 2002). All rocks exhibit evidence of a strong 1.815 to 1.810 Ga metamorphic overprint resulting from collision and overthrusting of the Flin Flon–Glennie Complex (Ashton *et al.*, 1999b; Bickford *et al.*, 2002). Rare fault-bounded lozenges, 10 to 100 m wide and hundreds of metres long, within a shear zone in the Flin Flon Domain yielded similar U-Pb zircon ages of 2.52 and 2.50 Ga (David *et al.*, 1993), consistent with exhumation of a tectonic slice derived from the structurally underlying Sask Craton. The ca. 2.49 to 2.43 Ga suite is thought to have been emplaced during rifting of the Sask Craton away from an older cratonic mass. Differences in the main ages of magmatic and metamorphic events indicate that the Sask Craton was likely not derived from the Hearne or Superior cratons (Ashton *et al.*, 1999b; Bickford *et al.*, 2002). A recent geochronological study of granitic xenoliths in kimberlites from the buried central Sask Craton (Davis *et al.*, 1998), however, included an age of ca. 2.074 Ga. Since coeval rifting events are known in both the Hearne (Ansdell *et al.*, 2000) and Superior provinces (Halls and Heaman, 2000), this may mark a major period of continental break-up. The study also produced a less well constrained age of about 2.79 Ga.

Reindeer Zone

The Reindeer Zone (Stauffer, 1984) occupies the southeastern third of the Shield area and comprises the Wathaman, Rottenstone, La Ronge, Kisseynew, Glennie and Flin Flon domains (Figure 10). It is a complex region of 1.92 to 1.83 Ga, subduction-generated, arc volcanic and plutonic rocks and interarc–successor-arc–marginal-basin sedimentary rocks (e.g., Lewry *et al.*, 1990; Syme *et al.*, 1998). These rock units are thought to have formed in a Pacific-scale ocean basin (Symons, 1998), termed the 'Manikewan Ocean' (Stauffer, 1984), which occupied the region between the Rae-Hearne, Superior and Sask cratons prior to terminal collision and formation of the 1.9 to 1.8 Ga Trans-Hudson Orogen. The isotopically evolved, 1.865 to 1.850 Ga Wathaman-Chipewyan Batholith (e.g., Meyer *et al.*, 1992; Corrigan *et al.*, 2000), a major Andean-type continental arc, was emplaced into the southeastern edge of the Hearne Craton due to west-directed subduction. The historic view is that early east-directed subduction led to accretion of the ca. 1.92 to 1.87 Ga La Ronge–Lynn Lake arc, which in turn led to a reversal in subduction polarity and emplacement of the batholith (e.g., Lewry *et al.*, 1990).

The 1.92 to 1.87 Ga, dominantly volcanic component of the southeastern Reindeer Zone is interpreted as an aggregate of distinct arc and ocean-floor tectonostratigraphic assemblages, which were tectonically amalgamated to form the 'Amisk collage' by about 1.87 Ga (Lucas *et al.*, 1996). Circa 1.870 to 1.845 Ga, juvenile, tonalitic to granitic arc plutons stitch many of the tectonostratigraphic assemblages and are thought to represent one or more successor arcs developed around an evolving protocontinent. Although this model was formulated in the relatively weakly deformed and metamorphosed region around Flin Flon, all indications are that it can be extended westward into the more intensely deformed and metamorphosed volcanoplutonic rocks of the western Flin Flon and adjacent Glennie domains. For this reason, the 1.92 to 1.845 Ga volcano-

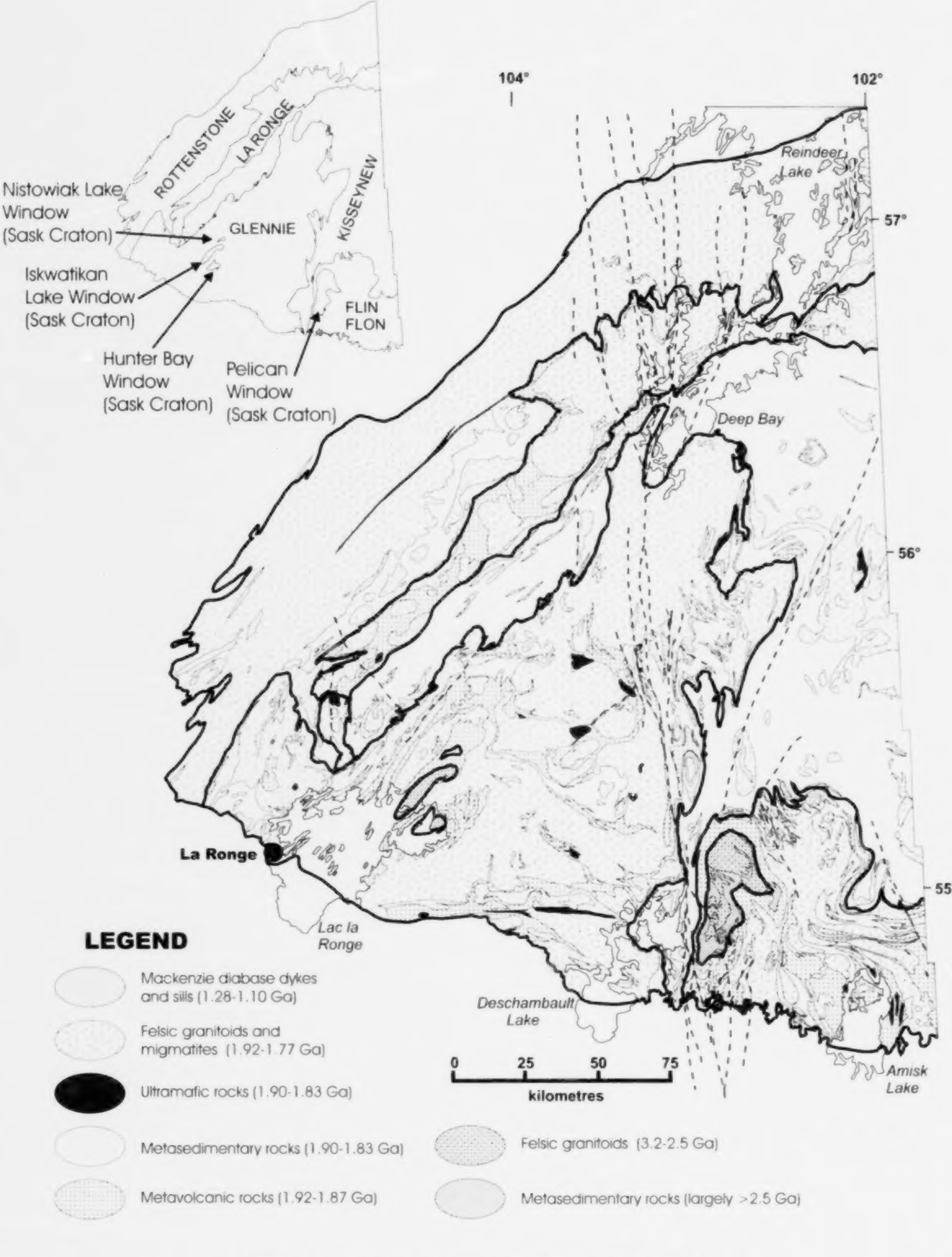

ROTTENSTONE
LA RONGE
KISSEYNEW
GLENNIE
FLIN FLON
Nistowiak Lake Window (Sask Craton)
Iskwatikan Lake Window (Sask Craton)
Hunter Bay Window (Sask Craton)
Pelican Window (Sask Craton)
104°
102°
57°
56°
55°
Reindeer Lake
Deep Bay
La Ronge
Lac la Ronge
Deschambault Lake
Amisk Lake
0
25
50
75
kilometres
LEGEND
Mackenzie diabase dykes and sills (1.28-1.10 Ga)
Felsic granitoids and migmatites (1.92-1.77 Ga)
Ultramafic rocks (1.90-1.83 Ga)
Metasedimentary rocks (1.90-1.83 Ga)
Metavolcanic rocks (1.92-1.87 Ga)
Felsic granitoids (3.2-2.5 Ga)
Metasedimentary rocks (largely >2.5 Ga)

Figure 10 – Simplified geology of the southern Reindeer Zone.

plutonic arc and ocean-floor rocks of the southeastern Reindeer Zone are collectively termed the 'Flin Flon–Glennie Complex' (Ashton *et al.*, 1997).

Tectonic amalgamation of the Amisk Collage, widespread emplacement of the 1.87 to 1.845 Ga successor-arc plutons, and inferred accretion of the Flin Flon–Glennie Complex to the Rae-Hearne Craton and accreted La Ronge arc complex together led to widespread uplift and deposition of fluvial to shallow marine sandstones of the 1.85 to 1.83 Ga McLennan-Sickle and Missi groups. More distal sediments were deposited as marine turbidites of the Burntwood Group in the Kisseynew Domain. It has been suggested that these Burntwood Group turbidites accumulated in a backarc basin (Ansdell *et al.*, 1995).

Models charting the mechanics and timing of the terminal collision continue to evolve, and some fundamental relationships remain unsubstantiated. An example is the timing of collision between the La Ronge and Flin Flon–Glennie arc complexes, which is traditionally considered to have occurred after the Sask Craton collision (e.g., Ansdell *et al.*, 1995). Current data are insufficient, however, to rule out the idea that the two arc complexes collided before the Sask Craton collision, which is thought to have occurred ca. 1.845 to 1.83 Ga, based on the cessation of arc magmatism, the intrusion of dioritic dikes crosscutting early mylonites, and the earliest metamorphic ages (Ashton *et al.*, 1999b). As noted above, the Archean Sask Craton structurally underlies most rocks of the Reindeer Zone (Lewry *et al.*, 1990; Ansdell *et al.*, 1995).

The Reindeer Zone, as indicated above, has been subdivided into a number of domains (Figure 10), based largely on the pioneering work of Lewry and Sibbald (1980) and Macdonald and Broughton (1980). The following domain framework builds upon these earlier contributions.

Wathaman Domain

The Wathaman Batholith (Fumerton *et al.*, 1984), formerly part of the Rottenstone Domain, has been afforded domain status due to its size and prominent role in the orogen. It can be traced continuously into Manitoba, where it is termed the 'Chipewyan Batholith' and is even more extensively developed. In Saskatchewan, compositions generally range from monzogranite to quartz diorite, and the dominant K-feldspar-megacrystic quartz monzonite phase varies only in the size and proportion of megacrysts. The northwestern margin of the 1.865 to 1.855 Ga (Meyer *et al.*, 1992; Corrigan *et al.*, 2001) batholith is marked by the Needle Falls and Parker Lake shear zones in the south and central parts; in the north, however, it intrudes Archean gneisses of the Peter Lake Domain. To the southeast, it is emplaced into Paleoproterozoic rocks of the Rottenstone Domain. The batholith has continental-arc affinities (Meyer *et al.*, 1992), and εNd values in all but the extreme southeast are strongly negative (MacHattie, 2001), consistent with emplacement through Archean rocks of the Hearne Craton. The Wathaman Batholith is thought to broadly stitch the suture between the Archean Rae-Hearne Craton and Paleoproterozoic accreted oceanic terranes of the Trans-Hudson Orogen, although one occurrence of Archean rocks is known from the Rottenstone Domain east of the batholith (Bickford and Hill, 2000).

Rottenstone Domain

The Rottenstone Domain has been redefined, in part because the area occupied by the intrusive Wathaman Batholith has been assigned domain status, but also to amalgamate 1) the lower to middle amphibolite facies sedimentary gneisses of the Crew Lake Belt (formerly in the La Ronge Domain) with their apparently correlative, upper amphibolite facies equivalents in the 'Tonalite-Migmatite Complex' (Lewry *et al.*, 1981; Ray, 1981; Gilboy, 1982b; Harper, 1990); and 2) the ca. 1.9 Ga volcanic rocks of the Clements Island Belt with volcanic rocks of similar age in the La Ronge Domain. Transition from the Crew Lake Belt to the Tonalite-Migmatite Complex is accompanied by a sharp increase in the proportion of injected melt leucosome and by the change from roughly circular to elongate pluton shape (Lewry *et al.*, 1981). Nevertheless, the domain remains heterogeneous, incorporating 1) rare Archean inliers (Bickford and Hill, 2000), presumably of the Hearne Craton; 2) a 1.89 to 1.88 Ga diorite-tonalite-granodiorite-granite intrusive suite named the Crowe Island Complex (Corrigan *et al.*, 1998, 2001); 3) at least two pre-Wathaman, gneissic to migmatitic supracrustal successions (Harper, 1986; Corrigan *et al.*, 1998); 4) intrusive orthogneiss derived from a ca. 1.86 to 1.85 Ga (Bickford *et al.*, 1986; Van Schmus *et al.*, 1987; Kyser and Stauffer, 1995), pre- to syntectonic, quartz diorite–tonalite–granodiorite suite (possible outliers of the Wathaman Batholith); and 5) 1.830 to 1.815 Ga syntectonic leucotonalite to granite intrusions (Clarke *et al.*, 2002). Slightly negative εNd values and detrital zircon studies (Ansdell *et al.*, 1999; Clarke *et al.*, 2002) suggest that detritus for the Rottenstone sedimentary rocks came both from the Archean Hearne Craton to the west and from juvenile Paleoproterozoic rocks to the east.

The eastern boundary of the Rottenstone Domain is marked by the transition from dominantly sedimentary to dominantly volcanic supracrustal rocks. Although the placement of this boundary is relatively straightforward in the central part of the domain, it is somewhat arbitrary in the northeast and southwest due to the structural interleaving of sedimentary and volcanic rocks. In the southeast, an apophysis of the Rottenstone Domain separates the southwestern end of the La Ronge Domain from the more highly metamorphosed 'Nemeiben

Zone', which is now assigned to the Glennie Domain in order to emphasize the continuity of map units.

At the northeastern end of the domain, in the recently studied Reindeer Lake area, the Crew Lake Belt has been subdivided into the upper amphibolite facies, dominantly siliciclastic Milton Island and Park Island sedimentary assemblages (Figure 11). Minor, ca. 1.90 Ga, mafic to felsic volcanic rocks are structurally interleaved in the Clements Island area, as is the ca. 1.89 Ga Crowe Island Intrusive Complex (Corrigan *et al.*, 1998, 2001). The **Milton Island Assemblage** comprises finely graded and thinly layered psammitic to pelitic gneisses, which are temporally constrained by 2.83 to 1.86 Ga detrital zircons (Corrigan *et al.*, 1998; Ansdell *et al.*, 1999; Maxeiner, 1999; Maxeiner *et al.*, 2001). The **Park Island Assemblage** (Corrigan *et al.*, 1998) includes basal conglomerate and partly cross-bedded feldspathic psammite, which structurally and stratigraphically overlie the Milton Island Assemblage and the volcanoplutonic rocks. The Looney Lake conglomerate, located about 100 km to the southwest, along the northwestern boundary with the La Ronge Domain, is thought to represent the basal unit of a correlative succession (Harper, 1985, 1986a).

Pre-1.87 Ga deformation in the Tonalite-Migmatite Complex (Bickford *et al.*, 1987) has been attributed to accretion of the La Ronge Arc to the eastern margin of the Hearne Craton via southeast-directed subduction (Bickford *et al.*, 1990; Meyer *et al.*, 1992); however, it could alternatively result from intra-oceanic terrane amalgamation, or accretion of an as-yet unidentified older arc complex hidden in the Rottenstone Domain (Tran, 2001).

Early regional deformation includes development of a foliation-gneissosity (D1) and two phases of isoclinal

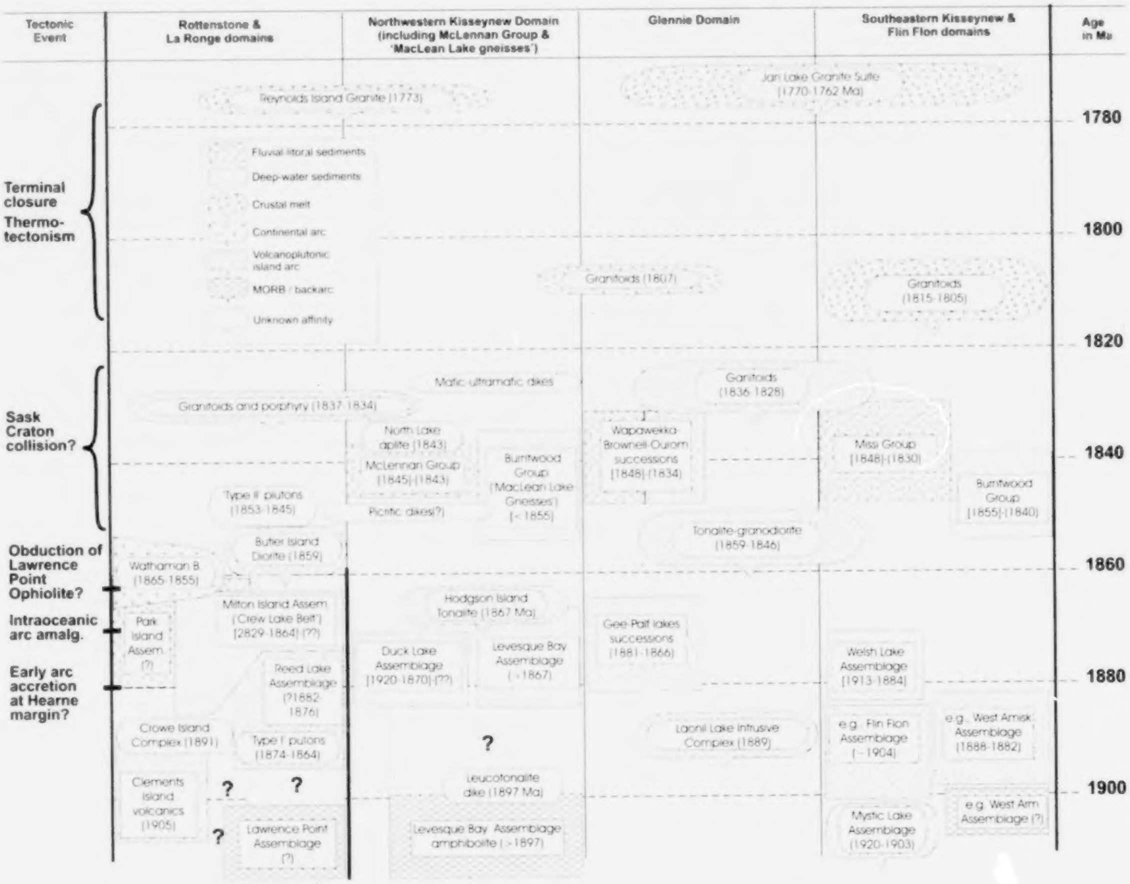

Tectonic Event
Rottenstone & La Ronge domains
Northwestern Kisseynew Domain (including McLennan Group & 'MacLean Lake gneisses')
Glennie Domain
Southeastern Kisseynew & Flin Flon domains
Age in Ma
1780
1800
1820
1840
1860
1880
1900
Terminal closure
Thermo-tectonism
Sask Craton collision?
Obduction of Lawrence Point Ophiolite?
Intraoceanic arc amalg.
Early arc accretion at Hearne margin?
Reynolds Island Granite (1773)
Jan Lake Granite Suite (1770-1762 Ma)
Fluvial-littoral sediments
Deep-water sediments
Crustal melt
Continental arc
Volcanoplutonic island arc
MORB / backarc
Unknown affinity
Granitoids (1807)
Granitoids (1815-1805)
Mafic-ultramafic dikes
Granitoids and porphyry (1837-1834)
Ganitoids (1836-1828)
North Lake aplite (1843)
McLennan Group (1845)-(1843)
Burntwood Group ('MacLean Lake Gneisses') (<1855)
Wapawekka-Brownell-Ourom successions (1848)-(1834)
Missi Group (1848)-(1830)
Burntwood Group (1855)-(1840)
Type II plutons (1853-1845)
Picritic dikes(?)
Tonalite-granodiorite (1859-1846)
Butler Island Diorite (1859)
Wathaman B. (1865-1855)
Milton Island Assem ('Crew Lake Belt') (2829-1864)-(??)
Hodgson Island Tonalite (1867 Ma)
Park Island Assem. (?)
Gee-Palf lakes successions (1881-1866)
Duck Lake Assemblage (1920-1870)-(??)
Levesque Bay Assemblage (>1867)
Welsh Lake Assemblage (1913-1884)
Reed Lake Assemblage (?1882-1876)
Crowe Island Complex (1891)
Type I plutons (1874-1864)
?
Laonil Lake Intrusive Complex (1889)
e.g. Flin Flon Assemblage (~1904)
e.g. West Amisk Assemblage (1888-1882)
Clements Island volcanics (1905)
?
?
Leucotonalite dike (1897 Ma)
?
Lawrence Point Assemblage (?)
Levesque Bay Assemblage amphibolite (>1897)
Mystic Lake Assemblage (1920-1903)
e.g. West Arm Assemblage (?)

Figure 11 – Lithostructural history of the Reindeer Zone. Dark lines indicate inferred unconformities and circles indicate overlying conglomerates. Dark arrows indicate inferred thrust faults. Overprinting of circles on other features implies intrusive relationships. All ages are U-Pb zircon ages and are from Corrigan* et al. *(2001) and Ansdell* et al. *(1999). Age of McLennan Group aplite is from L.M. Heaman, as reported in Kyser* et al. *(1992).

northeast-trending folding (D2 and D3) that resulted in type 3 fold interference (Lewry *et al.*, 1981). The resultant northeast-trending regional fabric was modified by open to close, north-trending D4 folds and subsequent strike-parallel and north-trending D5 faults. The D1-D4 deformations took place under amphibolite facies metamorphic conditions between about 1.835 and 1.815 Ga (Clarke *et al.*, 2002), although metamorphic zircons as young as 1.795 Ga have been recognized in the Milton Island Assemblage (Ansdell *et al.*, 1999).

La Ronge Domain

The extent of the La Ronge Domain has been significantly diminished due to 1) incorporation of the dominantly sedimentary rocks on its former western side in the adjacent Rottenstone Domain; 2) amalgamation of higher grade gneisses in the 'La Ronge Horseshoe' with contiguous rocks in the Glennie Domain to the southeast; and 3) grouping of dominantly sedimentary rocks of the McLennan and MacLean Lake belts with similar rocks of the Kisseynew Domain to the east (Figure 10). Thus, the term 'La Ronge Domain' is now used only for the 'Central Metavolcanic Belt', which is dominated by volcanoplutonic rocks that extend northeastward into Manitoba as the Lynn Lake Belt. The domain comprises 1) 1.90 to 1.86 Ga (Bickford *et al.*, 1986; Lewry *et al.*, 1987; Corrigan *et al.*, 2001) volcanic, sedimentary and synvolcanic plutonic rocks; 2) 1.87 to 1.83 Ga felsic to ultramafic arc-type plutons; and 3) minor 1.77 Ga granitoids (Corrigan *et al.*, 2001).

Recent work completed in the Reindeer Lake area (Figures 10, 11; Harper, 1996; Maxeiner, 1996; Maxeiner *et al.*, 2001; Corrigan, *et al.*, 1998, 1999, 2000) delineated a mafic-ultramafic 'Lawrence Point Assemblage' and a younger, mainly intermediate to felsic 'Reed Lake Assemblage'. The >1.88 Ga **Lawrence Point Assemblage** (Maxeiner, 1997) consists of a middle to upper amphibolite facies succession of ultramafic tectonite, pillow basalts, pelite, exhalative horizons and oxide facies iron formation. Based on the lithological make-up and geochemical signature of the mafic and ultramafic rocks, the assemblage is interpreted as a dismembered ophiolite (Maxeiner *et al.*, 1998, 2001).The **Reed Lake Assemblage** (Maxeiner, 1997) comprises middle amphibolite facies, intermediate to felsic volcanic and pyroclastic rocks interbedded with, and laterally grading into, a thick succession of reworked, shallow marine to partly subaerial volcanic rocks. It is built on top of the Lawrence Point Assemblage and has characteristics typical of tholeiitic to calc-alkaline island-arc settings (Maxeiner *et al.*, 2001). Felsic volcanism at ca. 1.88 Ga in the Waddy Lake area to the southwest (Bickford *et al.*, 1986; Harper *et al.*, 1986) is believed to be broadly coeval.

Along strike to the southwest, the proportion of rock types changes and the metamorphic grade is generally lower (Harper, 1985; Harper *et al.*, 1986; Thomas, 1993a). The Lower Waddy Lake Mafic-Ultramafic Assemblage, also recognized as a possible ophiolitic assemblage (Fox and Johnston, 1981; Harper, 1998a), may represent the base of the volcanic complex (Harper, 1984, 1985) and is considered correlative with the Lawrence Point Assemblage. Calc-alkaline intermediate and felsic volcanic rocks similar to those of the Reed Lake Assemblage are more prevalent around Waddy Lake, but tholeiitic mafic volcanic rocks predominate westward and southwestward to Star Lake. Farther south, in the Star-Otter lakes area, intermediate volcaniclastic rocks are slightly more prevalent than mafic rocks, and felsic varieties represent less than 10% of the succession. Low-potassium tholeiitic and calc-alkaline compositions occur in about equal amounts (Watters and Pearce, 1987; Thomas, 1993a).

Intrusions seen throughout the domain are broadly grouped (Thomas, 1985a; Harper, 1985; Harper *et al.*, 1986) into 1) composite or multiphase, gabbro and diorite to granite plutons; 2) relatively homogeneous, granodiorite to granite plutons; and 3) small homogeneous intrusions of quartz-rich leucogranite and leucogranodiorite. All are strongly calc-alkaline, and trace-element and Sr-isotope data are consistent with magma generation in a volcanic-arc setting.

An early layer-parallel schistosity (D0), exhibited by supracrustal xenoliths in the 1.859 Ga Butler Island Diorite (Maxeiner, 1997; Corrigan *et al.*, 2001), may be attributed to intra-oceanic amalgamation processes, or to accretion of the La Ronge or an older, unidentified arc complex to the Hearne Craton. The main regional foliation is generally subparallel to variably preserved primary layering, and is considered axial planar to tight to isoclinal D1 folds. A weak, moderately to steeply plunging, down-dip stretching lineation commonly accompanies D1 deformation. In the southwestern La Ronge Domain, tight to isoclinal D1 folds are truncated by the Little Deer Lake Pluton, the marginal dioritic phase of which is juvenile and has a Pb-evaporation age of 1.854 Ga (Kyser and Stauffer, 1995). A second, steeply northwest-dipping to vertical foliation is axial planar to northeast-trending, doubly plunging, tight to isoclinal D2 folds. Northeast-trending high-strain zones, some of which are gold bearing (e.g., Byers Fault), are probably D2 structures.

The D2 structures are overprinted by open to close, north-trending D3 folds with steeply east-dipping axial surfaces, and by upright, northeast-trending D4 folds. These D3 and D4 generations of folding are similar in orientation to late folding in the southeastern Reindeer Zone of Saskatchewan and may be coeval.

Central parts of the domain were metamorphosed at upper greenschist to middle amphibolite facies conditions, although upper amphibolite facies conditions were attained locally and near the domain boundaries. These conditions persisted throughout D1-D2 tectonism (Thomas, 1993a) and produced 1.82 to 1.80 Ga zircon ages (Kyser and Stauffer, 1995) and 1.81 to 1.78 Ga monazite and titanite ages (Thomas and Heaman, 1994; Corrigan, 2001).

Kisseynew Domain

The Kisseynew Domain is flanked by the La Ronge–Lynn Lake Domain to the north and the Flin Flon Domain to the south, with one arm extending southwestward (the former 'MacLean Lake Belt') to separate the La Ronge and Glennie domains. It is more voluminous in Manitoba, where it is truncated at the Churchill-Superior Boundary Zone (Zwanzig, 1990). The core of the domain is dominated by graphite-bearing, gneissic to diatexitic pelite and psammopelite of the 1.855 to 1.84 Ga (Machado and Zwanzig, 1995; David *et al.*, 1996) **Burntwood Group**, and intrusive 1.84 to 1.83 Ga successor-arc(?) and 1.815 Ga anatectic granitoids (Gordon *et al.*, 1990; Ashton *et al.*, 1999).

Boundaries between the Kisseynew and adjacent volcanoplutonic domains are marked by the transition from dominantly sedimentary to dominantly volcanoplutonic rocks. Consequently, the extensive margins of the Kisseynew Domain comprise a heterogeneous mixture of structurally interleaved core rocks and older (ca. 1.90 to 1.85 Ga) volcanic, plutonic and derived sedimentary rocks from the adjacent arc complexes. The boundaries are further complicated by the lithological similarity of moderately to highly metamorphosed, broadly synvolcanic (Heaman *et al.*, 1993; Ansdell and Stern, 1997) pelitic rocks of the volcanoplutonic domains (e.g., Welsh Lake Assemblage of Reilly, 1993; Duck Lake Assemblage of Maxeiner, 1997) to those of the younger Burntwood Group. Partly coeval conglomerate–feldspathic psammite successions that unconformably overlie the volcanoplutonic rocks in the adjacent domains (e.g., Missi Group) extend into the marginal zone as psammitic gneisses and are viewed as alluvial to shallow marine facies equivalents of the Burntwood Group (Syme *et al.*, 1998). The metamorphic grade is generally upper amphibolite facies, with patchy distribution of granulite facies assemblages. Repeated episodes of nappe-style tectonism preclude determination of original true thicknesses.

In the southern Reindeer Lake area, two largely sedimentary assemblages were delineated in the northern marginal zone of the domain. The **Duck Lake Assemblage** (Maxeiner, 1997, 1998) is a predominantly psammitic to pelitic, partly calcic sedimentary succession situated to the southeast and structurally below the Lawrence Point Assemblage. It lies along strike with, and is equivalent to, parts of the 'MacLean Lake Gneisses' (Harper *et al.*, 1986; Thomas, 1993a), which are described as a mixed succession of sedimentary gneisses and minor amphibolites, deposited in a littoral environment in which coarse and sandy alluvial-plain deposits were mixed with limy and argillaceous marine sediments. Lewry (1984) regarded the 'MacLean Lake Gneisses' as a telescoped remnant of a fore-arc basin. The age of the syn- to late-volcanic Duck Lake Assemblage is constrained by 1.92 to 1.87 Ga detrital ages (Stern *quoted in* Maxeiner *et al.*, 2000) and by the intrusive 1.867 Ga Hodgson Island Tonalite (Maxeiner *et al.*, 2001).

A similar succession of mixed sedimentary gneisses in the Deep Bay and Brenton Island areas of Reindeer Lake was named the **Levesque Bay Assemblage** (Corrigan *et al.*, 1999). It includes graphitic and partly sulphidic psammite and pelite, intermediate calc-silicate gneiss (interpreted as calcic sediments), minor marble and impure quartzite, and is likely correlative with the 1.88 to 1.87 Ga Duck Lake Assemblage. Crossbedded feldspathic psammite in the Sandford Island area of Reindeer Lake is also cut by the 1.867 Ga Hodgson Island tonalite (Maxeiner and Demmans, 2000) and represents a shallow-water component of the Levesque Bay Assemblage.

Thin units of >1.9 Ga (Corrigan *et al.*, 2001) banded amphibolite represent minor components of the Levesque Bay Assemblage and have been interpreted as altered and sheared mafic metavolcanic rocks. Farther southwest, highly deformed pillow structures were identified in several amphibolite occurrences (Johnston, 1969, 1970; Harper, 1996, 1997, 1998b), thus confirming their volcanic origin. They are cut by 1.897 Ga leucotonalite sheets (Corrigan *et al.*, 2001) and represent the oldest component of the assemblage. Geochemical investigations on equivalent amphibolites of the 'MacLean Lake Gneisses' (Hasanie and Harper, 1997; Hasanie, 1998; Harper, 1998b; Harper and Hasanie, 1999) revealed mid-ocean ridge basalt (MORB) affinities, and suggested a backarc setting. More recent studies confirmed a depleted normal MORB (N-MORB) to possible backarc geochemical signature for the Levesque Bay Assemblage amphibolites (Demmans *et al.*, 2002). The amphibolite and associated calc-silicate rocks likely represent remnants of oceanic crust, which was later blanketed by a thick succession of clastic sedimentary rocks.

The Levesque Bay Assemblage may have extensions along the Granville Lake structural zone in Manitoba, where amphibolites with MORB-like signatures occur along the boundary between the Burntwood and Sickle groups (Zwanzig *et al.*, 1999). It is likely that the northern flank of the Kisseynew Domain (i.e., the area occupied by the Duck Lake and Levesque Bay assemblages) represents an accretionary complex that records the closure of an intervening ocean basin between the La Ronge and Flin Flon–Glennie arc complexes (Maxeiner *et al.*, 2001). The suture is marked by the base of the Lawrence Point ophiolite (La Ronge Domain) and stitched by 1.837 Ga subalkaline to alkaline feldspar porphyry dikes.

The **McLennan Group** structurally and stratigraphically overlies the Levesque Bay and Duck Lake assemblages, and contains predominantly potassium feldspar–rich psammitic and conglomeratic rocks. The McLennan Group is interpreted as a ca. 1.843 to 1.83 Ga (L.M. Heaman, pers. comm., 1992; Kyser *et al.*, 1992; Ansdell and Yang, 1995) molasse, derived from a large and relatively homogeneous potassium feldspar–rich terrain. It lies along strike with identical rocks of the more extensive Sickle Group in Manitoba (McRitchie, 1974; Stauffer, 1990), which appears to contain both old and young sedimentary rocks. Rocks of the McLennan Group are locally terminated to the west by the McLennan Lake Tectonic Zone (MLTZ; Lewry, 1983; Thomas, 1985a, b) and are structurally overlain by the older Lawrence Point ophiolite and related volcanoplutonic terrains of the La Ronge Domain.

Northwest of the MLTZ, in the Waddy Lake and Jaysmith Lake areas, McLennan Group rocks unconformably overlie volcanoplutonic rocks of the La Ronge Domain (Harper, 1985, 1986a, 1997). Toward the southwestern end of the domain where the MLTZ dies out, primary sedimentary and volcanic features also confirm that the McLennan Group unconformably overlies older volcanoplutonic assemblages and the 'MacLean Lake Gneisses' (Lewry, 1983; M.W. Thomas, 1986; D.J. Thomas, 1987, 1993a; Maxeiner and Sibbald, 1995).

Pre-1.86 Ga deformation may have affected volcanoplutonic rocks in the domain margins, but post–Burntwood Group regional deformation began with development of the regional foliation-gneissosity (D1). This was followed by a southwest-vergent, multiphase deformational event (D2) involving widespread isoclinal folding and thrusting (Pearson, 1972; Lewry *et al.*, 1990), which resulted in the broad, regional, east-southeast-oriented structural trend exhibited throughout most of the domain. This early, ductile, southwest-vergent deformation lasted from about 1.83 to 1.80 Ga (Norman *et al.*, 1995) and is attributed to collision of the Sask Craton with the Flin Flon–Glennie Complex and adjacent sedimentary rocks of the Kisseynew Domain. The northeasterly trend and moderate to steep northwesterly dip of D1-D2 structures adjacent to the La Ronge Domain probably result from collision of the Sask Craton and accreted Flin Flon–Glennie Complex with the Hearne Craton and accreted La Ronge arc complex.

Metamorphism during the D1 event was sufficient to produce widespread partial melting, and ranged from upper amphibolite to granulite facies in all but the domain margins in the south, which were transitional with the lower to middle amphibolite facies rocks of the adjacent arc complexes. The relatively high temperature and medium pressure conditions were maintained during D2 time, and exceeded D1 conditions in the more weakly metamorphosed margins. Metamorphism resulting from the 1.83 to 1.80 Ga deformation produced 1.815 Ga anatectic granites (Gordon *et al.*, 1990) and zircon and monazite growth in the 1.818 to 1.80 Ga range (Ansdell *et al.*, 1999; Parent *et al.*, 1999).

Subsequent deformation included regional, tight to close, north-trending D3 folds with steeply east-dipping axial surfaces. A locally developed axial-planar foliation is most commonly defined by quartz flattening. Most mineral lineations and rodding in the southwestern arm are typically coaxial with third-generation minor folds, and generally plunge between 25 and 45° north to north-northeast. Open, upright, northeast-trending D4 folds and associated north-trending sinistral faults are considered postcollisional structures (Lewry *et al.*, 1990).

The McLennan Lake Tectonic Zone (Lewry, 1983; Thomas, 1985a, b) is a 0.2 to 2 km wide, gently to moderately northwest-dipping, high-strain zone marking the boundary between the Kisseynew and La Ronge domains. It extends to the northeast in the Reindeer Lake area as the Duck Lake Shear Zone (Maxeiner, 1998) and may be correlative with the Johnson Shear Zone in Manitoba (Beaumont-Smith, 2000). It probably originated as a northeast-vergent D2 thrust fault (Lewry, 1983), but also shows evidence of younger, dextral, strike-slip displacement at higher crustal levels (Thomas, 1993a).

Glennie Domain

The Glennie Domain is dominated by 1.89 to 1.83 Ga plutonic rocks, but also contains significant Paleoproterozoic supracrustal rocks related to the Trans-Hudson Orogen, as well as Archean rocks of the Sask Craton exposed in three small tectonic windows (the latter are described in the 'Sask Province' section, above). Recent work has shown that rocks of the northwestern Flin Flon Domain re-emerge in the Scimitar Lake area on the northern limb of a late northeast-trending synform cored by rocks of the Kisseynew Domain (Ashton, 1999). Since the former 'Scimitar Complex' was recently incorporated in the Glennie Domain, it follows that rocks of the Flin Flon Domain are continuous with those of the Glennie Domain and can be collectively referred to as the **Flin Flon–Glennie Complex**. Despite their continuity, distinct domain names have been retained for historical reasons and discussion purposes (Figure 10).

The western boundary of the Glennie Domain was originally placed at the Stanley Shear Zone, a subvertical belt of mylonites and overprinting brittle faults (Lewry, 1981a). It was recently moved westward due to the recognized continuity of gneissic to migmatitic rocks stretching from the west-central Glennie Domain southwestward into the Nut Bay (Lac La Ronge) area, which had been previously assigned to the La Ronge Domain (Ashton, 1999). In order to accommodate the extension of those same rocks farther westward into the Nemeiben Lake area (Lewry *et al.*, 1990), the entire 'La Ronge Horseshoe', comprising the Meraste Zone, Nut Bay Belt and Nemeiben Zone, is now being incorporated into the Glennie Domain. Assuming that the La Ronge and Flin Flon–Glennie arc complexes were at one time distinct entities, a tectonic boundary must now separate them. Until new mapping reveals the location of this discontinuity, the domain boundary is placed at the somewhat arbitrary contact between the orthogneiss-dominated Nemeiben Zone and the paragneiss-dominated Crew Lake Belt. Farther north, the Glennie-Kisseynew domain boundary is placed at the lithological transition from dominantly volcanoplutonic to dominantly sedimentary rocks.

The Glennie Domain contains deformed elongate and arcuate belts of largely upper greenschist to lower amphibolite facies supracrustal rocks in a predominantly granitoid terrain (Figure 10). As in the Flin Flon Domain, there are two distinct supracrustal successions. The first is dominated by ca. 1.881 to 1.866 Ga (Van Schmus *et al.*, 1987; Heaman *et al.*, 1991, 1992; Slimmon, 1994), mafic to intermediate flows and fragmental, synvolcanic sedimentary and subordinate felsic volcanic rocks, and is considered broadly correlative with the 'Amisk Collage'. Limited geochemical investigations suggest a tholeiitic, primitive island-arc regime for at least some of these rocks (Slimmon, 1994; Delaney, in prep.), but the succession likely represents a number of amalgamated tectonic settings, as in the Flin Flon Domain. This older supracrustal succession is intruded by both ca. 1.89 to 1.87 Ga synvolcanic arc-type plutons (e.g., the 1.889 Ga Laonil Lake Intrusive Complex; Chiarenzelli, 1989) and ca. 1.86 to 1.846 Ga gabbro-diorite-tonalite-granodiorite successor-arc plutons (Bickford *et al.*, 1987; Delaney *et al.*, 1988; Chiarenzelli, 1989).

The second supracrustal succession is dominated by metamorphosed conglomerate, grit and psammite, but locally includes mafic to felsic volcanic and volcaniclastic rocks. There are several occurrences, including the **Wapawekka and Brownell Lake successions** in the south, the **Ourom Group** in the east and the **Pine Lake Group** in the central domain, where the volcanic-bearing, dominantly psammitic succession lies unconformably atop older supracrustal rocks (Lewry, 1977b; Delaney, 1992). A maximum age of 1.848 Ga is provided by the Nielson Lake Pluton, which is unconformably overlain by the Ourom Group on the western side of the Tabbernor Fault (Elliott, 1995), and by the oldest detrital zircons, of identical age, from psammites at Wapawekka Lake (McNicoll *et al.*, 1992) and in the Ourom Group (Delaney *et al.*, 1988). The Pine Lake succession includes a 1.838 Ga sodic rhyolite (McNicoll *et al.*, 1992), and 1.837 Ga detrital zircons are known from psammopelite at Sadler Lake (Heaman *et al.*, 1991), indicating either immediate reworking of the felsic volcanic rocks or diachronous deposition. A 1.834 Ga minimum age constraint is provided by the intrusive Maynard Creek porphyry in the Brownell Lake area (McNicoll *et al.*, 1992). It is part of a 1.836 to 1.828 Ga suite of late arc-type intrusions (Van Schmus *et al.*, 1987; McNicoll *et al.*, 1992) that is considered broadly correlative with the ca. 1.842 to 1.825 Ga suite in the Flin Flon Domain.

Given the similarities in lithological make-up, age and implied depositional setting, together with the structural evidence supporting the correlation of Flin Flon and Glennie domain rocks, it is probable that this second, dominantly siliciclastic succession is correlative with the Missi Group of the Flin Flon and Kisseynew domains. The succession probably graded from 'continental' facies, represented by fluvial to alluvial conglomerates, grits and psammites in the Flin Flon and Glennie domains, to a shallow-marine facies, comprising psammitic, psammopelitic and rare pelitic rocks in the Kisseynew Domain. It has been suggested, based on their gradational lithological transition and on their similar age constraints, that the shallow-marine facies of the Missi Group is transitional into the dominantly pelitic 1.855 to 1.84 Ga (Machado and Zwanzig, 1995; David *et al.*, 1996) Burntwood Group in the Kisseynew Domain (Stauffer, 1990).

The major tectonic activity related to the Trans-Hudson Orogen was followed by the emplacement of minor, 1.770 to 1.727 Ga, late- to post-tectonic granites and pegmatites (Chiarenzelli, 1989; Durocher *et al.*, 1993), the majority of which fall in the 1.770 to 1.762 Ga range and are considered part of the Jan Lake Granite Suite.

As elsewhere in the Reindeer Zone, early deformation consisted of two phases of tight to isoclinal folding (D1 and D2). In the east, much of this can be attributed to accretion of the Flin Flon–Glennie Complex to the Sask Craton, whereas, in the west, collision of the Flin Flon–Glennie Complex with the Hearne Craton and previously accreted La Ronge Domain arc complex controlled the early structural history. Subsequent tight, north-trending D3 folds and superposed open, northeast-trending D4 folds produced the modified dome-and-basin fold interference pattern responsible for exposing the Archean tectonic windows.

In the Glennie Domain, the structural base of the Flin Flon–Glennie Complex is represented by the **Nistowiak and Hunter Bay gneisses**, which mantle the tectonic windows through which the Archean Sask Craton is exposed. The protomylonitic to blastomylonitic rocks are derived from plutonic and migmatitic protoliths, and are considered tectonically equivalent to rocks of the Pelican Thrust Zone. The **Guncoat Gneisses** are mylonites derived from psammopelitic migmatites. They represent the sole of a major thrust nappe ('Wapassini Allochthon' of Lewry *et al.*, 1990) and mark a higher-crustal-level D2 splay off the Pelican Thrust Zone.

The northern margin of the Glennie Domain is also marked by a broad D2 mylonite zone (Harper, 1998b). Dismemberment of a premylonitic leucosome, developed in upper amphibolite to granulite facies Burntwood Group pelites, results in a characteristic porphyroclastic texture. A prominent stretching lineation, together with delta-winged porphyroclasts, indicates south-southwest-directed thrusting of the 1.89 to 1.87 Ga supracrustal rocks over the Flin Flon–Glennie Complex. Granitoid dikes, emplaced late during the mylonitization, yielded a U-Pb zircon age of 1.808 Ga (Harper *et al.*, 2000). A late, undeformed granitic pegmatite (ca. 1.78 Ga) that intrudes the mylonitic granitoid gneisses yielded a strongly negative εNd value (Harper *et al.*, 2000), characteristic of post-collisional granites and pegmatites throughout the Reindeer Zone. The low value indicates that the pegmatites were at least partially derived from melting of Archean basement, and from this it can be inferred that the Sask Craton extends at least this far northward at depth and that it was emplaced prior to 1.78 Ga.

Flin Flon Domain

The Flin Flon Domain, situated in the southeastern part of the exposed Reindeer Zone in Saskatchewan (Figure 10), is dominated by Paleoproterozoic volcano-plutonic and subordinate, broadly synvolcanic pelitic rocks of the Flin Flon–Snow Lake belt. The term 'Flin Flon Domain' was originally restricted to the greenschist and lower amphibolite facies rocks of the immediate Flin Flon area, but was recently expanded to incorporate the upper amphibolite facies northwestern extension of continuous, dominantly volcanoplutonic rocks (i.e., the former 'Attitti Block'). Broad compositional and temporal similarity of the volcanoplutonic 'Hanson Lake' and 'Northern Lights' volcanic successions, together with recognition of the intervening Sturgeon-weir Shear Zone as a higher-crustal-level splay of the Pelican Thrust, led to further expansion of the Flin Flon Domain to incorporate the former 'Hanson Lake Block' (Ashton, 1999; Maxeiner *et al.*, 1999). Due to its inclusion in the former 'Hanson Lake Block', the Pelican Window, comprising Archean rocks of the underthrust Sask Craton (*see* 'Sask Province' section), has also been incorporated into the Flin Flon Domain.

Recent work has shown that the ca. 1.910 to 1.875 Ga, dominantly basaltic succession within the Flin Flon Domain includes several distinct tectonic assemblages (Figure 11; e.g., Thomas, 1991; Reilly, 1995), representing arc, backarc, ocean plateau and mid-ocean ridge environments, which were tectonically amalgamated at about 1.87 Ga (Lucas *et al.*, 1996). The following brief description is based on the synthesis of a recent NATMAP study centred in the Flin Flon–Snow Lake area, where upper greenschist facies metamorphic conditions have allowed excellent preservation of primary structures (Syme *et al.*, 1998).

The **Flin Flon Arc Assemblage** of the immediate Flin Flon area comprises mainly subaqueous basalt and basaltic andesite (Bailes and Syme, 1989). Subordinate terrigenous turbidites, MORB-like rift basalts and shoshonitic turbidites are attributed to episodes of arc rifting and intra-arc basin development (Stern *et al.*, 1995a, b; Lucas *et al.*, 1996). A synvolcanic gabbro–diorite–quartz diorite–tonalite suite (e.g., the 1.886 Ga Cliff Lake Pluton) intrudes as sills, dikes and plutons (Whalen *et al.*, 1999).

Within the Flin Flon Arc Assemblage is a small tectonic sliver of 1.920 to 1.903 Ga calc-alkaline, massive to layered, amphibolite facies, granodioritic to dioritic orthogneiss, termed the '**Mystic Lake Evolved-arc Assemblage**' (Reilly, 1990, 1991; Thomas, 1991; Reilly *et al.*, 1995). Initial εNd values of -3.1 to -6.1 and 2.67 to 2.56 Ga xenocrystic zircons suggest that it may represent a midcrustal tectonic slice of an arc built on Archean crust (Stern *et al.*, 1992, 1993; Stern and Lucas, 1994; Lucas *et al.*, 1996).

To the west, the **Birch Lake Arc Assemblage**, comprising massive plagioclase-phyric and amygdaloidal mafic flows with minor ash and lapilli tuffs (Reilly, 1991; Slimmon, 1991; Thomas, 1991; Reilly *et al.*, 1994, 1995), has tholeiitic arc affinities and may represent a structurally disrupted extension of the Flin Flon Assemblage.

The **West Amisk Arc Assemblage** comprises 1) a lower, tholeiitic, pillowed to emergent mafic sequence and a high-level, felsic volcanic dome complex (Harper, 1993); 2) overlying greywacke turbidites and interfingering shallow-water felsic complexes; and 3) an upper sequence of andesitic flows and volcaniclastic rocks (Walker and Watters, 1982; Ashton, 1990; Reilly, 1992, 1993, 1994). The succession is attributed to an episode of arc rifting followed by development of an intra-arc basin (Lucas *et al.*, 1996).

The **Sandy Bay Ocean-Plateau Assemblage**, situated on the eastern side of Amisk Lake, separates the Flin Flon and Birch Lake arc assemblages from the West Amisk Arc Assemblage. It is an approximately 3 km thick, monotonous sequence of subaqueous tholeiitic basalts and synvolcanic sills of unknown age (Reilly *et al.*, 1994; Slimmon, 1995). Stern *et al.* (1995) suggested an ocean-plateau or ocean-island origin for the basalts, based on their geochemical characteristics and juvenile Nd isotopic signature.

Farther west, the Sturgeon-weir Shear Zone juxtaposes the West Amisk and Hanson Lake arc assemblages. The latter includes primitive arc tholeiites to evolved 1.875 Ga calc-alkaline arc rocks. In the east (i.e., Hanson Lake), a mixed suite of subaqueous to subaerial, dacitic to rhyolitic and subordinate intercalated mafic volcanic rocks is overlain by greywackes (Maxeiner *et al.*, 1999). The arc assemblage is somewhat younger than most arc volcanism to the east and includes 1.873 to 1.870 Ga synvolcanic granites (e.g., Hanson Lake Mine Road Granite).To the west (i.e., east of Sarginson Lake), the undated 'Northern Lights' volcanic succession comprises tholeiitic, arc-type, pillowed mafic flows and felsic to intermediate volcaniclastic rocks and greywackes that can be traced continuously westward to Wapawekka Lake in the south-central Glennie Domain (Maxeiner *et al.*, 1999).

A gabbro-diorite-tonalite-granodiorite suite of juvenile-arc plutons (e.g., Annabel Lake Pluton), ranging in age from ca. 1.870 to 1.845 Ga, stitches many of the faults bounding distinct volcanic assemblages and is thought to represent one or more successor arcs developed around the evolving Flin Flon–Glennie protocontinent.

At about 1.845 Ga, fluvial and alluvial sandstones and conglomerates of the **Missi Group** (Stauffer *et al.*, 1975) were being unconformably deposited upon the Amisk Collage as molasse. Their age is bracketed by ca. 1.848 Ga detrital zircons and by ca. 1.84 Ga intrusive rocks, which cover a much wider compositional range than their predecessors and include the ca. 1.842 Ga ultramafic to mafic and syenitic Boundary Intrusions, the ca. 1.841 Ga plagioclase-phyric tonalites, and the 1.838 Ga Boot Lake Monzodiorite and Phantom Lake Granite-Granodiorite (Ansdell and Kyser, 1990; Heaman *et al.*, 1992).

This period of late arc-type magmatism, which continued until about 1.830 to 1.825 Ga, was followed by the emplacement of syncollisional anatectic granites and pegmatites in more highly metamorphosed areas during the main ca. 1.815 to 1.800 Ga regional metamorphic event. This was followed by regional uplift and cooling, recorded by 1.81 to 1.78 Ga titanite ages (David *et al.*, 1993; Machado *et al.*, 1999), prior to emplacement of ca. 1.77 Ga, late- to post-tectonic, medium-grained to pegmatitic granite, termed the '**Jan Lake Granite Suite**' in Saskatchewan (Bickford *et al.*, 1987). This suite includes beryliferous pegmatites in the Hanson Lake area and, at Jan Lake, includes minor mafic material with evidence of magma mingling (Ashton and Shi, 1994). Similar relationships in the 1.76 Ga Nueltin Granite–Pitz Rhyolite Suite of the Rae and Hearne provinces of Nunavut were attributed to the emplacement of basaltic magma along brittle faults in the crust and the resulting generation of crustal melts (Peterson and van Breeman, 1999). The Tabbernor Fault and late brittle reactivation of the Sturgeon-weir Shear Zone may have provided the conduits for basaltic magma ascent in the Reindeer Zone.

The northern domain boundary is somewhat arbitrarily placed at the lithological transition from dominantly volcanoplutonic rocks of the Flin Flon–Glennie Complex in the south to dominantly pelitic rocks of the Kisseynew Domain. Placement of the boundary is difficult due to the similarity of broadly synvolcanic pelitic rocks in the south to the ca. 1.85 to 1.84 Ga Burntwood Group that dominates the Kisseynew Domain.

The earliest deformation recognized in the Flin Flon area produced shear zones and more widespread penetrative fabrics attributed to ca. 1.87 Ga intra-oceanic amalgamation of the 'Amisk Collage' (Ryan and Williams, 1999). The first regional phase of deformation (D1) in the weakly metamorphosed portion of the Flin Flon Domain involved isoclinal folding and associated northwest-verging thrust faults (Thomas, 1992), which Syme *et al.* (1998) attributed to 1.88 to 1.840 Ga intra-arc shortening. Alternatively, much of this deformation could have been caused by accretion of the Flin Flon–Glennie Complex to the Hearne Craton and previously accreted La Ronge arc complex, which is thought to have taken place ca. 1.85 Ga, based on the cessation of continental-arc magmatism in the Wathaman Batholith. Regardless of the cause, uplift and erosion of the Amisk Collage and 1.87 to 1.845 Ga successor-arc plutons followed, resulting in ca. 1.85 to 1.83 Ga deposition of the Burntwood and Missi groups, which were also affected by the latter stages of D1 deformation (Syme *et al.*, 1998; Ryan and Williams, 1999). In the higher grade northern Flin Flon Domain, D1 is thought to have taken place under upper amphibolite facies conditions, since the resulting penetrative foliation is partially defined by melt leucosome.

The second deformational event (D2) at Flin Flon resulted in north- to northeast-trending, west- to southwest-verging, tight to isoclinal folds and an axial-planar penetrative schistosity (Thomas, 1993b). It is attributed to collisional shortening and crustal thickening, resulting from collision of the Flin Flon–Glennie Complex with the Sask Craton ca. 1.84 to 1.805 Ga. In the higher grade gneisses of the northern Flin Flon Domain, D2 produced at least one phase of isoclinal folding defined by the early D1 gneissosity, along with southwest-verging thrust faults characterized by kilometre-scale high-strain zones and down-dip stretching lineations that generally plunge gently to moderately northeastward, unless re-oriented by later folding. These structural discontinuities delineate a series of nappes that are rooted in the Pelican Thrust (Lewry *et al.*, 1990), which is the sole fault along which the Flin Flon–Glennie Complex tectonically overrode the Sask Craton (Ashton *et al.*, 1996). The dextral-reverse Sturgeon-weir Shear Zone is considered a splay off the Pelican Thrust.

The timing of the Flin Flon–Glennie collision with the Sask Craton has been placed at ca. 1.84 to 1.83 Ga based on 1) involvement of the ca. 1.85 to 1.83 Ga Burntwood and Missi groups and the 1.845 to 1.830 Ga granite-granodiorite plutons; 2) cessation of all arc-type magmatism by 1.83 to 1.825 Ga; and 3) the crosscutting relationship of a syntectonic 1.826 Ga dike in D2 mylonites (Hartlaub *et al.*, 1997). The regional northeast-plunging stretching lineation attributed to D2 tectonic transport can be observed in the 1.826 Ga dike, as well as in pegmatite dikes as young as 1.806 Ga (Ashton *et al.*, 1992), although it is much less intense than in the mylonites they intrude.

Peak metamorphic conditions were attained during the D2 deformational event and are generally attributable to tectonic thickening during D1-D2. There is evidence of metamorphism as early as 1.83 Ga, but peak conditions based on metamorphic zircon (with an estimated closure temperature in excess of 800°C; Heaman and Parrish, 1991 and references therein) fall in the 1.82 to 1.80 Ga range. Cooling below the 650°C minimum melting curve took place during D3 time, based on the 1.81 to 1.78 Ga range of metamorphic monazite and titanite dates (with closure temperatures of about 700° and 600°, respectively). Thus, by the end of D2, the general configuration of metamorphic zones had been established, although subsequent deformation led to significant modification of local individual isograds, whereas the approximately 20 m.y. of temperatures in excess of the minimum melting curve resulted in widespread recrystallization.

Following development of the east-west D2 structural fabric attributed to the Sask Craton–Flin Flon–Glennie Complex collision, rocks of the southeastern Reindeer Zone were subjected to two further phases of regional folding (Lewry *et al.*, 1990). The first (D3) produced close to tight, north- to northwest-trending, steeply inclined folds with gentle to moderate northerly plunges and moderate to steep east-dipping axial planes. A locally developed axial-planar fabric is variously defined by quartz flattening and rare granitic segregations, biotite, cordierite and/or fracture cleavage. Mineral and intersection lineations are variably developed collinear to minor fold axes. The D3 folding is tentatively attributed to deformation resulting from collision of the Superior Craton with the Sask Craton and accreted Flin Flon–Glennie Complex. Development of a D3-type foliation in granites similar to the Jan Lake Granite Suite is consistent with D3 lasting from about 1.80 to 1.77 Ga.

Regional and minor folds developed during D4 time are open to close structures with gentle to moderate northeast-plunging fold axes and steep to upright axial planes. An axial-planar foliation, defined by quartz flattening or biotite, is rarely developed in fold hinges. The D4 folds locally deform Jan Lake–type pegmatite dikes in the northeastern Glennie Domain, suggesting that they resulted from postcollisional shortening after 1.77 Ga.

The **Tabbernor Fault** is a narrow, north-trending, steeply dipping to vertical belt of heterogeneous strain marked by ductile to brittle high-strain zones, tight north-south periclinal folds and local steep metamorphic gradients (Macdonald, 1975a; Sibbald, 1978). Recent studies suggest a long and complicated history (Wilcox, 1990, 1991; Lewry *et al.*, 1991; Elliott, 1993; Ashton and Balzer, 1995). Ductile D2 thrust faults and fold traces in the Glennie Domain are rotated into the zone, implying that it formed as an intracontinental fault during D3 time. Preservation of abundant Ourom Group rocks in the eastern block may indicate initial east-side-down displacement, but alternatively may result from high-amplitude D3 folding. Regardless, the main ductile shearing event involved east-side-up D3 displacement, based on the sharp eastward increase in metamorphic grade that can be traced along the segment of the fault stretching from the Phanerozoic unconformity to at least the Churchill River. Doming of Sask Craton rocks in the Pelican Window, together with this vertical displacement on the Tabbernor Fault, effectively trapped the intervening Ourom and Burntwood group strata and older Paleoproterozoic rocks. Continued D3 east-west shortening produced heterogeneous strain, with 1) continued east-side-up ductile and brittle-ductile high-strain zones; 2) rare down-dip stretching lineations, best developed in anatectic granites and pegmatite dikes; 3) doubly plunging periclinal folds; and 4) associated rotation of the northeast-plunging D2 stretching lineation into north- and south-plunging orientations. Since this vise-like configuration is restricted to the area in which the Sask Craton is at relatively shallow crustal levels, this intense D3 deformation dies out to the north. During subsequent D4 northwest-southeast shortening, the Tabbernor Fault was reactivated as a sinistral, brittle to brittle-ductile fault and extended southward to at least Cumberland House and northward to the Northwest Territories boundary (Byers, 1962; Elliott, 1995). Subtle episodic displacements continued up to the Quaternary (Giroux, 1995).

Although the Tabbernor Fault Zone appears to have been initiated as a D3 structure, its scope and orientation suggest that it represents a higher structural level ramification of a pre-existing structure at depth. Aeromagnetic data from the southeastern part of Saskatchewan show that the Tabbernor Fault overprints a wide aeromagnetic low that appears to coincide either with the eastern boundary of the Sask Craton below Phanerozoic strata or, more likely, with a major internal structural discontinuity, since the Sask Craton is now thought to extend into Manitoba at depth (Hajnal *et al.*, in prep.). Thus, the Tabbernor Fault probably represents a higher-crustal-level Paleoproterozoic ramification of a reactivated underlying discontinuity that was thrust into place, along with the Sask Craton, during the D2 event.

Synthesis of the Reindeer Zone

The interaction of at least three Archean cratons (Rae-Hearne-Wyoming, Superior and Sask-Dakota) has produced a much more complex tectonic scenario than is the case for simple two-craton continent-continent orogens. In fact, the Reindeer Zone probably owes its existence to the involvement of the competent Sask Craton, which effectively prevented the Rae-Hearne and Superior cratons from impinging during terminal collision. The excellent preservation of juvenile rocks in this strain shadow allows for a better examination of Paleoproterozoic tectonic processes, although several outstanding questions concerning the tectonic history of the Trans-Hudson Orogen remain unanswered.

Rifting of the Rae-Hearne Craton and opening of the Manikewan Ocean began at about 2.07 Ga, based on the age of the Courtenay-Cairns succession, and passive margin sedimentation on the craton is recorded in lowermost Wollaston Supergroup sedimentary rocks. Circa 1.92 to 1.87 Ga, volcanic and synvolcanic plutonic rocks in arc complexes throughout the Reindeer Zone record the earliest contraction of this ocean, which involved the amalgamation of rocks from several oceanic crustal settings, particularly for the 'Amisk Collage'.

The initial accretionary events at the eastern Hearne margin are not well understood. The existing model involves collision of the La Ronge arc complex due to east-dipping subduction, followed by a polarity reversal and emplacement of the ca. 1.86 to 1.85 Ga Wathaman Batholith as a continental magmatic arc above a west-dipping subduction zone. Recent workers (e.g., Tran, 2001) have questioned the need for early east-dipping subduction, and instead favour multiple west-dipping subduction zones to account for the early accretionary history, which is recorded only as early deformational fabrics in xenoliths within ca. 1.86 Ga plutons. Regardless, early accretion transformed the eastern Hearne margin into a foreland basin into which most of the Wollaston Supergroup was deposited. The cessation of Wathaman magmatism at ca. 1.85 Ga is generally attributed to impingement of the Flin Flon–Glennie Complex, although precise times for these events are difficult to determine due to uncertainties surrounding the time required for tectonic processes (e.g., the time required between collision and appearance or disappearance of continental arc magmas). Collision of the Flin Flon–Glennie Complex with the Hearne Craton and accreted La Ronge arc theoretically produced the deformation, uplift and erosion responsible for deposition of the 1.85 to 1.83 Ga alluvial–shallow-marine sedimentary rocks preserved in the McLennan, Sickle, Ourom, Wapawekka and Missi groups. Broadly coeval, deeper water facies rocks of the Burntwood Group are thought to have been deposited in a backarc setting (Ansdell *et al.*, 1995), which is supported by the presence of underlying oceanic crust, as inferred from the high gravity signature of the Kisseynew Domain. Widespread 1.85 to 1.83 Ga 'successor-arc' plutons indicate that subduction processes continued regionally during this time.

Collision of the Sask Craton with the Flin Flon–Glennie Complex, due to north-dipping subduction, probably began at ca. 1.84 Ga but lasted until 1.80 Ga, resulting in the D2 regional deformational event and the upper amphibolite to granulite facies metamorphic conditions that dominate much of the southeastern Reindeer Zone (ca. 1.815 to 1.805 Ga 'peak' conditions). It is unclear whether the Sask Craton also interacted with the Hearne Craton at this time or later, during terminal collision. A 1.822 Ga megacrystic granite gneiss collected from drillcore in the Regina area (Collerson *et al.*, 1988) may record this collision.

The cessation of arc magmatism at about 1.83 to 1.825 Ga presumably indicates ocean closure, although the southwest-verging deformation generally attributed to the Sask Craton–Flin Flon–Glennie collision is thought to have persisted until about 1.805 Ga. Thus, the north-trending D3 folding attributed to initial collision of the Superior Craton may have overlapped D2 deformation and delayed regional uplift. The plate readjustments leading to the final tectonic configuration probably occurred at ca. 1.77 Ga and resulted in widespread granitic magmatism and regional northeast-trending D4 folds.

Athabasca Basin

The Athabasca Basin covers about 100 000 km^2 in northern Saskatchewan and northeastern Alberta. The late Paleoproterozoic Athabasca Group lies unconformably on a basement regolith up to 50 m thick (Hoeve and Sibbald, 1978). It consists mainly of fluvial clastic sedimentary rocks, which are about 1400 m thick in the central part of the basin (Ramaekers, 1979, 1990). Apart from faulting and local folding associated with thrusting or with the Carswell Structure, the strata are undeformed. Outliers of Athabasca sandstone, such as the one at Reilly Lake, indicate that the basin was formerly much more extensive.

Originally termed the Athabasca Sandstone (Fahrig, 1961), the Athabasca Group comprises eight formations (Figure 12). Fine- to coarse-grained, partly pebbly or clay-intraclast–bearing quartz arenites predominate, but conglomerate, mudstone and dolostone are also minor components (Ramaekers, 1990; Ramaekers *et al.*, 2001). At least four broadly fining-upward, unconformity-bound cycles can be distinguished: the Fair Point, Manitou Falls, Lazenby Lake–Wolverine Point, and Locker Lake–Carswell sequences (Table 2; Yeo *et al.*, 2001; Yeo *et al.*, 2002).

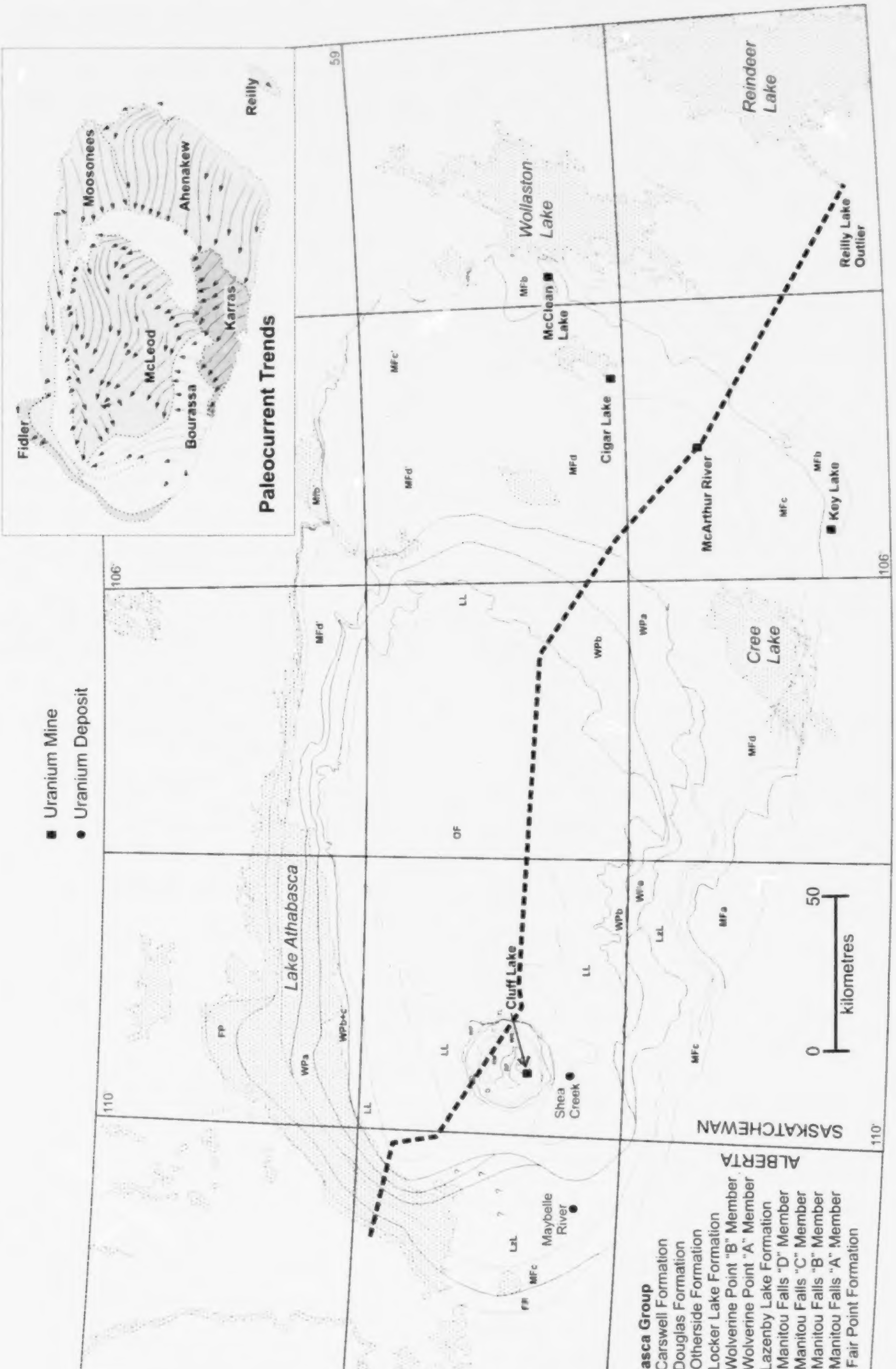

Uranium Mine
Uranium Deposit
Paleocurrent Trends
Fidler
McLeod
Bourassa
Karras
Ahenakew
Moosonees
Reilly
Lake Athabasca
Cluff Lake
Shea Creek
Maybelle River
Cree Lake
Wollaston Lake
Reindeer Lake
McClean Lake
Cigar Lake
McArthur River
Key Lake
Reilly Lake Outlier
FP
WPa
WPb+c
LL
LzL
MFc
MFa
WPb
OF
MFd
MFb
0
50
kilometres
59
58
110
106
SASKATCHEWAN
ALBERTA
Athabasca Group
C Carswell Formation
D Douglas Formation
OF Otherside Formation
LL Locker Lake Formation
WPb Wolverine Point "B" Member
WPa Wolverine Point "A" Member
LzL Lazenby Lake Formation
MFd Manitou Falls "D" Member
MFc Manitou Falls "C" Member
MFb Manitou Falls "B" Member
MFa Manitou Falls "A" Member
FP Fair Point Formation

Figure 12 – Simplified geology of the Athabasca Basin (after Ramaekers et al., 2001). Dashed line indicates line of section (see Figure 13).

Lithostratigraphy and paleocurrent patterns indicate deposition in seven deposystems (Table 2, Figures 12, 13; Ramaekers *et al.*, 2001). These reflect shifting loci of uplift and/or subsidence over time.

The Athabasca Group postdates the ca. 1.9 to 1.77 Ga Trans-Hudson Orogeny, and detrital zircons as young as 1.66 Ga have been recognized in the Wolverine Point Formation (Rainbird *et al.*, 2002). The strata have undergone several episodes of diagenetic alteration, one of which precipitated 1.70 to 1.65 Ga fluorapatite (Cumming *et al.*, 1987), providing a further constraint on the minimum age for deposition. The minimum age is provided by the intrusive 1.27 Ga Mackenzie dikes. The age of volcaniclastic grains and glass shards in the Manitou Falls and Wolverine Point formations is still unknown, but they may be derived from equivalents to the 1.755 Ga Pitz volcanic rocks of the Baker Lake Basin to the north.

Post-tectonic Features

Dikes and Late Intrusions

Quartz-bearing, clinopyroxene-plagioclase diabase-gabbro sills cut the Wathaman Batholith northeast of Dobbin Lake and at Tremblay Lake, and also occur between Oliver and Reindeer lakes, where they intrude rocks of both the Rottenstone and La Ronge domains. They are part of the 1.270 Ga Mackenzie suite (LeCheminant and Heaman, 1989; Hulbert *et al.*, 1993), which is also thought to include a southeast-trending set of diabase dikes that is known from drillcore and can be seen on aeromagnetic maps to extend across much of the Athabasca Basin. The approximately 2.5 km thick, near-horizontal Wollaston Lake seismic reflector underlying much of the eastern end of the Athabasca Basin is attributed to en échelon sets of Mackenzie sills (Mandler and Clowes, 1997). A dike-sill complex in the Cree Lake area (Ramaekers and Hartling, 1979; Quirt, 1993) appears to be part of the Mackenzie suite based on orientation, but the local presence of olivine is geochemically inconsistent and may indicate a distinct origin.

The 1.11 Ga (MacDougall and Heaman, 2002) Moore Lakes Complex, on the southeastern perimeter of the Athabasca Basin, comprises olivine diabase-gabbro sills that have intruded Wollaston Domain basement and the Athabasca Group (MacDougall and Williams, 1993).

Southward Extension of the Precambrian Shield beneath Phanerozoic Cover

In the southern two-thirds of Saskatchewan, Precambrian rocks are unconformably overlain by sedimentary rocks ranging in age from Middle Cambrian to Cretaceous. Most major tectonic elements known in the exposed Precambrian Shield, however, can be traced with a high degree of certainty southward below Phanerozoic cover using geophysical data sets and limited borehole information (e.g., Kreis *et al.*, 2000). A first-order lithostructural hierarchy (*see* aeromagnetic and gravity maps in back pocket) defines major crustal features of the buried and exposed Precambrian, namely 1) the Archean Rae, Hearne, Sask, and Wyoming cratons; 2) the Paleoproterozoic (ca. 1.9 to 1.8 Ga) Reindeer Zone; 3) the unmetamorphosed Swift Current Anorogenic Province (ca. 1.76 Ga); and 4) several boundary zones. Discussion of the sub-Phanerozoic Precambrian architecture focuses on the main crustal-scale breaks, as

Table 2 – Summary stratigraphic succession, Athabasca Group. The Tuma Lake Formation (Ramaekers, 1979, 1990) is now considered a part of the Locker Lake Formation that was uplifted around the western rim of the Carswell Structure. Dominant paleocurrent trends for each deposystem are indicated.

Formation	Lithology	Sedimentary environment	West Athabasca deposystems	East Athabasca deposystems
Carswell	Stromatolitic dolostone	Shallow marine or lacustrine		
Douglas	Black, red and green mudstone and sandstone	Lacustrine or shallow marine		
Otherside	Sandstone and siltstone	Fluvial or shoreface	McLeod (NW and W)	
Locker Lake	Pebbly sandstone	Fluvial		
		Disconformity		
Wolverine Point	Sandstone and siltstone	Fluvial and lacustrine	Bourassa (N)	
Lazenby Lake	Pebbly sandstone	Fluvial		
		Disconformity		
Manitou Falls	Sandstone, pebbly sandstone and conglomerate	Fluvial	Karras (NW)	Moosonees (W) Ahenakew (WNW)
		Disconformity		
Fair Point	Pebbly sandstone	Fluvial	Fidler (NW)	

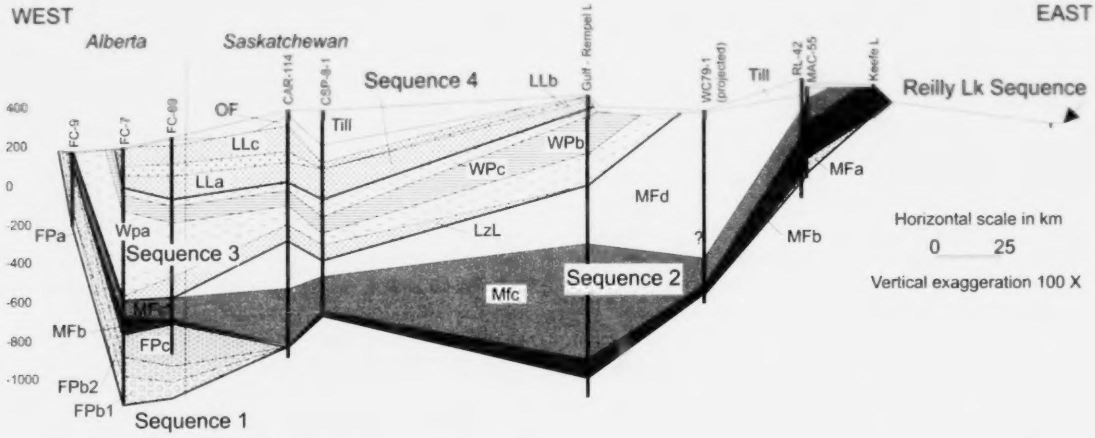


***Figure 13 – Cross-section of the Athabasca Basin* (after *Ramaekers, in prep.*). See *Figure 12* for location of section.**

they are potential zones of Phanerozoic reactivation, an important aspect in Phanerozoic sedimentation and the formation of structural traps for hydrocarbons. Neodymium model ages and U-Pb zircon ages are from Collerson *et al.* (1990) and Collerson *et al.* (1988), respectively, unless otherwise indicated.

The Precambrian unconformity dips to the southwest at approximately 2.8 to 4.8 m/km (Kreis *et al.*, 2000) until it reaches the northern margin of the present-day structural Williston Basin (approximately represented by the -1500 m contour on Figure 14), the configuration of which is largely the result of Laramide deformation. South of the -1500 m contour, the dip of the unconformity steepens from about 4.5 m/km to about 15.0 m/km at the Canada–United States border near Estevan. Maximum thickness of Phanerozoic sedimentary rocks in Saskatchewan is about 3200 m (at the border with the United States, 165 km south-southeast of Regina). In the centre of the Williston Basin, the sedimentary rocks are approximately 4900 m thick (about 75 km south-southeast of Williston in northwestern North Dakota).

Kreis *et al.* (2000) completed a re-evaluation of the sub-Phanerozoic Precambrian basement in southern Saskatchewan and outlined several geological domains (*see* aeromagnetic and gravity maps in back pocket), based on southward extrapolation of lithotectonic domains in the exposed shield, aeromagnetic and gravity data sets, new geological insights from NATMAP (e.g., Syme *et al.*, 1998) and geophysical interpretations from LITHOPROBE (e.g., Clowes, 1997). Limited amounts of direct lithological and geochronological information from these domains were derived from drillcore collected during hydrocarbon and mineral exploration (e.g., Thomas *et al.*, 1987; Hoffman, 1989; Nelson *et al.*, 1993; Jones *et al.*, 1993; Burwash *et al.*, 1993; Miles *et al.*, 1997). Interpretations of the sub-Phanerozoic Precambrian geology of southern Alberta (e.g., Ross *et al.*, 1995) and the northern United States (e.g., Baird *et al.*, 1996) have also provided a regional framework within which to integrate the Saskatchewan component of the Precambrian basement (*see* aeromagnetic and gravity maps in back pocket).

Beginning in the northwest, rocks of Lloyd Domain in the Rae Province are continuous beneath Phanerozoic cover, but are overprinted by the north-trending Clearwater magnetic high. Folding of the older, northeast-trending magnetic fabric in the eastern Lloyd Domain results in a northwestward trend in the west. This reoriented trend is dextrally offset by the Beatty River Fault to the north, but continues into Alberta (Figure 5; *see* aeromagnetic map in back pocket). The Lloyd Domain is bounded to the southeast by the Virgin River Shear Zone (Snowbird Tectonic Zone), whereas the Clearwater Domain may be truncated (Ross *et al.*, 1991) or dextrally offset, depending on placement of the shear zone and interpretation of magnetic highs. The internal structural fabric of the Clearwater Domain appears broadly coplanar with the Virgin River Shear Zone, suggesting coeval development. The 1.82 Ga Junction Granite, which cuts previously mylonitized rocks of the Virgin River Shear Zone but is itself weakly sheared, may be correlative with 1.86 to 1.80 Ga granitic rocks of the Rimbey magnetic high (Ross *et al.*, 1991, 1995) and with granitic rocks of the Clearwater Domain. All of these granites may be crustal melts that were emplaced episodically along the Snowbird Tectonic Zone and its splays.

Rocks of the Hearne Province display greater apparent continuity in their southward extension beneath Phanerozoic cover. The arcuate magnetic signature resulting from complexly folded, dominantly Archean orthogneisses of the Mudjatik Domain extends into Alberta. Nevertheless, weakly metamorphosed but undated supracrustal rocks, together with a ca. 2.2 Ga granite, are found in drillcore in its apparent southwestward extension, leading to a Paleoproterozoic designation for the Lacombe Domain (Ross *et al.*, 1991, 1995). It is possible that the Lacombe supracrustal rocks are correlative with the similarly undated Virgin Schist Group of the Virgin River Domain.

In the absence of an obvious geological cause for the aeromagnetic low that characterizes the eastern Mudjatik Domain on the exposed Shield, it is attributed to the polarized nature of aeromagnetic data, and is therefore thought to be an artifact of the magnetic high that typifies the Wollaston Domain. Nevertheless, a broader magnetic low along its southwestward extension has been delineated as the **Makwa Domain**, where four upper amphibolite to granulite facies orthogneisses and pelitic paragneisses, presumably correlative with the Archean basement and overlying Wollaston Supergroup, respectively, yielded Nd model ages of 2.99 to 2.69 Ga (Collerson *et al.*, 1990), and a charnockitic gneiss yielded a poorly constrained U-Pb zircon age of 2.48 Ga (Collerson *et al.*, 1988). The Makwa Domain appears correlative with the reworked Archean Loverna Block in Alberta (Ross *et al.*, 1991).

The Wollaston Domain also appears broadly continuous to the south. The linear magnetic high produced by a combination of basement orthogneisses and Wollaston psammitic paragneisses on the exposed shield continues to the Great Falls Tectonic Zone as the **Battlefords Domain**. It includes dioritic gneisses in the extreme southwest, which yielded Nd model ages of 3.32 to 3.19 Ga (Collerson *et al.*, 1990), and is considered broadly equivalent to the Archean orthogneiss-dominated Eyehill Domain in Alberta.

At its southern extent, the Battlefords Domain is ill defined, in part because of an apparently overprinting, northeast-trending magnetic fabric that is attributed to deformation within the **Great Falls Tectonic Zone** (O'Neil and Lopez, 1985). Most workers have placed this discontinuity at the southern limit of the broader zone presented here; however, the greater northern extent of the northeast-trending magnetic overprint on the north-trending Battlefords magnetic structures justifies expanding the Great Falls Tectonic Zone. This zone has historically been considered to be a ca. 1.8 Ga suture recording the amalgamation of the Hearne Craton with the Wyoming Craton to the south (Thomas *et al.*, 1987; Hoffman, 1989). This model is supported by the recent interpretation of north-dipping seismic reflectors at the inferred Wyoming-Hearne domain boundary as a relict subduction zone (Clowes, 2002). Nevertheless, this suture model continues to be questioned by workers favouring an intracontinental origin for the discontinuity (e.g., Boerner *et al.*, 1998). Neodymium model ages from three samples within the zone range from 2.84 to 2.58 Ga, confirming an Archean crustal origin. Coincidence between the inferred northern margin of the tectonic zone and the northwestern boundary of Cretaceous and Tertiary exposures between Maple Creek and Swift Current suggests that the structure may have been periodically re-activated. The small segment of crust south of the Great Falls Tectonic Zone has been designated the **Assiniboia Domain**.

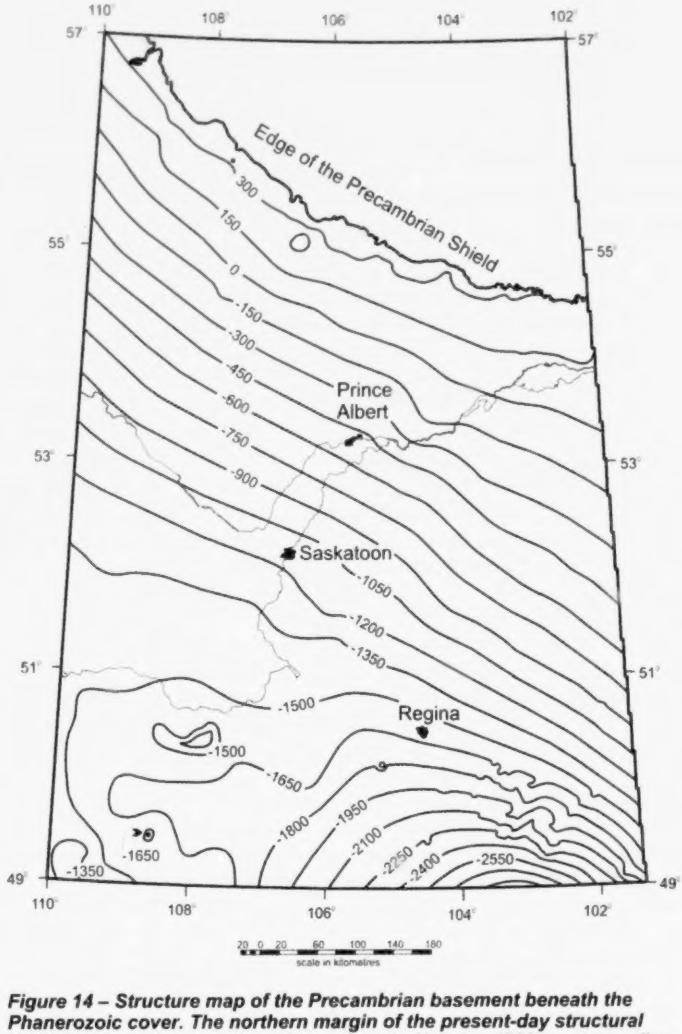


Figure 14 – Structure map of the Precambrian basement beneath the Phanerozoic cover. The northern margin of the present-day structural Williston Basin is approximately represented by the -1500 m contour line. Modified after Kreis et al. (2000).

To the west, in Alberta, northwest-trending 3.28 to 2.61 Ga orthogneisses of the Medicine Hat Block are truncated to the north by the northeast-trending Vulcan magnetic low, which incorporates ca. 2.63 Ga amphibolites (Ross *et al.*, 1991). The similarly oriented Matzhiwan magnetic high farther north contains 2.59 Ga granitoid rocks, which have been interpreted as part of a magmatic arc resulting from accretion of the Medicine Hat Block to the Loverna Block of the Hearne Craton. This view is supported by a second set of north-dipping reflectors thought to record another relict subduction zone (Clowes, 2002). The relationship between the Battlefords Domain in southwestern Saskatchewan and the Medicine Hat Block is unclear, due to their similarly oriented internal structures. Nevertheless, undeformed 1.76 Ga granites, felsic volcanic rocks and hypabyssal porphyries of the **Swift Current Anorogenic Province**, with Nd model ages ranging from 2.73 to 2.58 Ga, are found in the vicinity of both the Battlefords–Medicine Hat boundary and the Great Falls Tectonic Zone (Collerson *et al.*, 1990). Recent recognition of ca. 1.865 Ga, isotopically juvenile, arc-derived gneiss and diorite suggest that the Little Belt Mountain segment of the Great Falls Tectonic Zone incorporates a subduction complex that records the Paleoproterozoic amalgamation of the Medicine Hat Block and Wyoming Craton (Mueller *et al.*, 2002)

The subsurface extent of the Sask Craton is estimated from the distinct structural pattern seen immediately south of the exposed Reindeer Zone, where a seismically transparent 'block' is known at depth from LITHOPROBE transects (Lucas *et al.*, 1993; Lewry *et al.*, 1994). Rare tectonic windows to Archean rocks and strongly negative εNd values from ca. 1.77 Ga post-tectonic granites (Steinhart *et al.*, 1997) confirm the presence of the Sask Craton beneath most of the exposed Reindeer Zone. The Sask Craton is subdivided based on magnetic signature; however, it should be noted that the resulting boundaries locally cut across magnetic structural trends and do not closely follow the trends of gravity data, which are relatively high throughout the craton. From north to south, the Sask Craton has been subdivided into the Tobin, Smeaton, Humboldt, and Weyburn domains.

The highly magnetic **Tobin Domain** contains a single upper amphibolite to granulite facies pelitic gneiss that yielded a Nd model age of 3.04 Ga. The main east-southeast-trending structural fabric in the Tobin Domain results from southwest-verging structures attributed to collision between the Sask Craton and Flin Flon–Glennie Complex. This trend appears to overprint the dominantly northward structural trend that characterizes the rest of the Sask Craton, and is in turn modified by a north-trending phase of folding, which is presumably correlative with the D3 phase of deformation on the exposed Shield.

The weakly magnetic **Smeaton Domain** contains extensive oxide facies iron formation, with interlayered marble and marl, that is characterized by a strong, well-defined magnetic anomaly. The age of these supracrustal rocks is unknown, but their relatively low metamorphic grade, together with a relatively young Nd model age of 2.29 Ga from biotite-muscovite schist located near the iron formation, may indicate that they represent a thin veneer of Paleoproterozoic rocks overlying Archean basement. The Smeaton Domain also hosts the Fort-à-la-Corne kimberlites. Four granitic xenoliths within the kimberlites yielded U-Pb crystallization ages of 3.22, 2.81 to 2.75, 2.59 to 2.45, and 2.07 Ga (Davis *et al.*, 1998), the latter of which was also associated with a metamorphic event in one rock. Minor metamorphic mineral growth took place at 1.81 Ga, but the main thermotectonic event occurred at 1.77 to 1.76 Ga, coeval with the late- to post-tectonic Jan Lake Granite Suite in the exposed Reindeer Zone and with felsites of the Swift Current Anorogenic Province, but 30 to 40 m.y. after peak metamorphism in the exposed part of the Trans-Hudson Orogen. This apparently indicates that tectonic loading and metamorphism related to the collision between the Sask Craton and Flin Flon–Glennie Complex barely reached this far into the Sask Craton, but that the later collision of the Superior Craton produced widespread tectonic reworking at ca. 1.76 Ga. The dominantly northward trend displayed by the magnetic fabric is attributed to a north-trending phase of folding, perhaps of this ca. 1.76 Ga age.

The **Humboldt Domain** is defined by more highly magnetic rocks, including dioritic to granodioritic orthogneisses in the west with Nd model ages of 2.68 to 2.63 Ga. Internal structures are dominantly north trending, and have been deformed by north-trending megafolds. To the southeast, the highly magnetic Humboldt Domain grades into the weakly magnetic **Weyburn Domain**. A megacrystic garnetiferous granitic gneiss near the Humboldt-Weyburn domain transition yielded a minimum U-Pb age of 1.82 Ga and a Nd model age of 2.52 Ga, and may record collision between the Sask and Hearne±Wyoming cratons. Seismic studies some 50 km south of the Canada–United States border (Baird *et al.*, 1996) have revealed a zone similar in seismic character to the Sask Craton. It has been termed the Dakota Block, and is considered broadly correlative.

Sub-Phanerozoic continuation of Reindeer Zone rocks in a small triangular area west of the Sask Craton is obvious from aeromagnetic data, so no new domain designation has been assigned. An orthogneiss retrieved from core obtained southwest of Lac La Ronge yielded a Nd model age of 2.75 Ga (Prokopiuk and Ansdell, 2000), suggesting that previously unrecognized tectonic windows or slices exposing Archean Sask Craton rocks may be present south of, and within, the 'La Ronge Horseshoe'.

East of the Sask Craton, Reindeer Zone rocks extend a considerable distance southward to form the variably magnetic **Cumberland Domain**. A mylonite from the weakly magnetic Preeceville area yielded a Nd model age of 2.25 Ga, consistent with derivation from a Paleoproterozoic rock that has been partially contaminated by Archean crustal material. An upper amphibolite to granulite facies tonalitic orthogneiss from the Moose Mountain area yielded a well-constrained U-Pb crystallization age of 1.86 Ga, suggesting a juvenile arc-type origin.

The Sask Craton is rimmed by weakly magnetic boundary zones that are thought to result from collisional deformation. In the north and east, the **Wapawekka-Estevan Domain** represents the transitional boundary between the Sask Craton and the Reindeer Zone. Its northern segment is characterized by a well-defined structural fabric, which mantles the inferred interface between the Sask Craton, the Reindeer Zone and Phanerozoic cover rocks. Amphibolites from this area, which yielded Nd model ages of 2.35 and 2.04 Ga, are thought to represent moderately contaminated Paleoproterozoic rocks of the Flin Flon–Glennie Complex, whereas a younger pegmatitic granite with a Nd model age of 3.01 Ga probably resulted from the partial melting of Archean Sask Craton rocks at depth (Prokopiuk and Ansdell, 2000). An orthogneiss from the western segment of the domain yielded a Nd model age of 2.71 Ga, supporting the inferred presence of Archean Sask Craton rocks. The less magnetic eastern segment of the domain displays mainly north-trending structures and includes porphyritic microgranite and intermediate granulite in the Tisdale area, with Nd model ages of 2.88 to 2.53 Ga. The latter of these also yielded a well-constrained 1.79 Ga metamorphic zircon age. Cordierite gneiss from the Weyburn area, near the southern end of the domain, yielded Nd model ages of 2.89 Ga. Since the Sask Craton is now thought to extend beneath most of the Reindeer Zone, based on seismic and isotopic evidence (Z. Hajnal, pers. comm., 2002), its inferred outline on aeromagnetic maps is thought to broadly represent its subsurface extent at the Phanerozoic unconformity. Nevertheless, the magnetically quiet eastern boundary may represent a fundamental Archean discontinuity at depth, the northern end of which was reactivated during Paleoproterozoic time as the Tabbernor Fault.

The Sask Craton is flanked to the west by the **Hearne-Reindeer-Sask Boundary Zone**, which coincides with the more than 500 km long Reindeer Magnetic Quiet Zone (Burwash *et al.*, 1993; Green *et al.*, 1985). It comprises mixed psammopelitic paragneisses and granitoid rocks in the exposed western Glennie (i.e., La Ronge Horseshoe) and Rottenstone domains, and appears to truncate both Glennie Domain rocks to the east and the Wathaman Batholith to the west (assuming that it was originally present). Two granitoid rocks from just south of the Precambrian-Phanerozoic unconformity yielded Nd model ages of 2.55 and 2.42 Ga. The latter of these, tonalitic gneiss, also yielded a poorly constrained U-Pb zircon age of 1.91 Ga, suggesting that it originated as a weakly contaminated synvolcanic intrusion.

The Hearne-Reindeer-Sask Boundary Zone also broadly coincides with the approximately 2000 km long North American Central Plains Conductivity Anomaly (NACP; Reitzel *et al.*, 1970), which has been attributed to sulphide-bearing metasedimentary rocks deposited in a fore-arc setting prior to collision and underplating of the La Ronge arc complex beneath the Hearne Craton (Jones *et al.*, 1993). A wide zone of crustal-scale, west-dipping seismic reflectors that separates the Sask and Hearne cratons immediately south of the exposed 'La Ronge Horseshoe' (Lewry *et al.*, 1994) is consistent with this model, but contrasts with the situation south of the United States border, where the Dakota Block is separated from the Wyoming Province by dominantly east-dipping reflectors (Baird *et al.*, 1996). This discrepancy, together with the change in position of the NACP from the Dakota-Wyoming and Sask-Hearne boundaries in the south to the older La Ronge–Hearne boundary in the north, implies a diachronous origin related to at least two sutures. The apparently truncating nature of the Reindeer Magnetic Quiet Zone implies that collision of the Sask-Dakota craton took place after the main period of deformation along the Great Falls Tectonic Zone (Boerner *et al.*, 1998).

Just as reactivation of the Great Falls Tectonic Zone may have influenced the present contact between Cretaceous and Tertiary strata in southwestern Saskatchewan, northwest-trending structural discontinuities, probably related to the Hearne-Reindeer-Sask Boundary Zone, appear to control the northeastern edge of The Missouri Coteau. A more restricted, northwest-trending exposure of Cretaceous and Tertiary rocks in Grasslands National Park appears spatially related to a coplanar aeromagnetic lineament of possibly similar origin.

In the far southeast, the Superior-Reindeer Boundary Zone, marking north- to northeast-trending deformation related to collision of the Superior Craton and Reindeer Zone rocks, has been approximated using aeromagnetic data extending farther east into Manitoba. It coincides with a gravity high (*see* above), which is likely due to ultramafic rocks similar to those that occur along strike to the northeast (e.g., Baragar and Scoates, 1987; Hulbert *et al.*, 1994).

A more rigorous treatment of late crosscutting aeromagnetic discontinuities in the sub-Phanerozoic Precambrian Shield of Saskatchewan can be found in Miles *et al.* (1997).

Meteorite Impact Structures

Although the dynamic nature of orogeny, erosion and deposition, and weathering collectively work to obscure major depressions in the Earth's surface, a number of features, both in the northern exposed Shield and in the Phanerozoic south, have been interpreted as meteorite impact structures. The largest of these is the **Carswell Structure** of the western Athabasca Basin (Harper, 1982, 1983). This approximately circular structure is about 35 km in diameter and exposes the Carswell and Douglas formations on its outer annulus. Older Athabasca Group rocks of the William River Subgroup form an inner ring and, in places, are highly disturbed, inverted and thrust faulted, presumably due to the impact. An uplifted basement core, about 18 km in diameter, is faulted both tangentially at the perimeter and by offsetting radial faults. The basement and Williams River Subgroup rocks are intruded by the Cluff Breccia, which is generally considered to be an impact rock (Robertson and Grieve, 1975; Harper 1982, 1983). Whole-rock Ar/Ar dating has yielded estimates of 513 to 416 Ma (Von Einsiedel, 1982) and 515 to 365 Ma (Bell, 1985) for the Cluff Breccia, whereas the whole-rock K-Ar technique provided ages of 486 ± 55 and 467 ± 28 Ma from two fractions of a heterogeneous sample (Wanless *et al.*, 1968). Other evidence for impact includes deformation lamellae in quartz, shatter cones and striations, and fractured cobbles (e.g., Currie, 1967; Pagel, 1975; Tapaninen, 1975, 1976; Harper, 1983). Impact is estimated to have been produced by an asteroid about 1 km in diameter (Pagel, 1975), based on the size of the central uplift.

The **Deep Bay Structure** at the southern end of Reindeer Lake is about 11 km in diameter (Gilboy, 1980c; Johnston, 1983) and up to 220 m deep. Cretaceous sedimentary rocks have been recovered from drillholes into the bottom of the lake, and indicate an age of about 100 Ma (Innes *et al.*, 1964).

The ca. 210 Ma **Gow Lake Structure** of the west-central Rottenstone Domain has a diameter of about 5 km (Gilboy, 1982b) and is one of the smallest impact structures in Canada to have a central uplift. Parts of the uplifted core, which is exposed as Calder Island, consist of kärnäite (fine, cherty, lava-like material) and suevite (rubbly 'pyroclastic' rock; Robertson and Grieve, 1975).

In southern Saskatchewan, petroleum exploration has led to the discovery of two impact structures. The Early Jurassic **Viewfield Structure**, located east of Estevan, is 2 to 3 km in diameter and was first identified by seismic surveys in the early 1970s (Sawatzky, 1972). Drilling for oil and gas revealed a 100 m deep circular feature excavated into Mississippian bedrock and surrounded by a raised rim of breccia, now known to be the ejecta blanket. The rocks underlying the crater are intensely fractured (Grieve *et al.*, 1998) as would be expected in a meteorite impact. The crater rim facies has produced substantial quantities of oil and gas.

The **Maple Creek Structure**, barely exposed on the northern flank of the Cypress Hills east-southeast of Maple Creek, is about 6 km in diameter. A highly disturbed central uplift of Cretaceous sedimentary rocks was identified in several drillholes (Gent *et al.*, 1992) and indicates an age of about 75 Ma (Grieve *et al.*, 1998).

Phanerozoic

A northward-thinning wedge of sedimentary rocks, ranging in age from Cambrian to Tertiary (Figure 15; *see also* colour stratigraphic chart, back pocket), underlies the southern two-thirds of the province. It is part of the sedimentary package deposited in the Western Canada Sedimentary Basin on the western side of the North American Craton (the Precambrian Shield). On a regional scale, two distinct depositional-tectonic phases are recognized in the development of this basin. An initial passive continental-margin phase (Cambrian to Middle Jurassic) was characterized in Saskatchewan by deposition of a basal clastic unit and a thick sequence of platform carbonates and evaporites. It was followed by a convergent-margin phase (Middle Jurassic to Eocene) that resulted in establishment of a foreland basin and deposition of thick accumulations of clastic sediments derived from the emerging Cordilleran Mountain Belt (Stott and Aitkin, 1993; Price, 1994). Deposition and erosion of sedimentary strata in Saskatchewan were also strongly influenced by the episodic downwarping of the intracratonic Williston Basin, vertical movements of its peripheral structural blocks, smaller scale block faulting related to reactivation of basement structures, and eustatic sea-level changes. These factors, together with postdepositional folding, faulting and salt-dissolution effects, largely govern the outcrop and subcrop distribution of remaining Phanerozoic strata, and the location of such economically important resources as oil, natural gas, coal and potash. In the vicinity of three towns in southern Saskatchewan, Maple Creek, Elbow and Viewfield, the sedimentary sequence is disrupted and forms structures interpreted as being the result of meteorite impact (Grieve *et al.*, 1998). Surficial evidence of these structures is evident over the Maple Creek and Elbow structures but is absent over the Viewfield structure. The origin of the Elbow Structure is debatable.

Paleozoic

Sandstones, siltstones and shales of the Deadwood (Middle Cambrian to Lower Ordovician) and Winnipeg (Middle Ordovician) formations (Figure 15) make up the basal clastic unit of Phanerozoic strata in Saskatchewan (Figure 16), except in the northwest where, 10 to

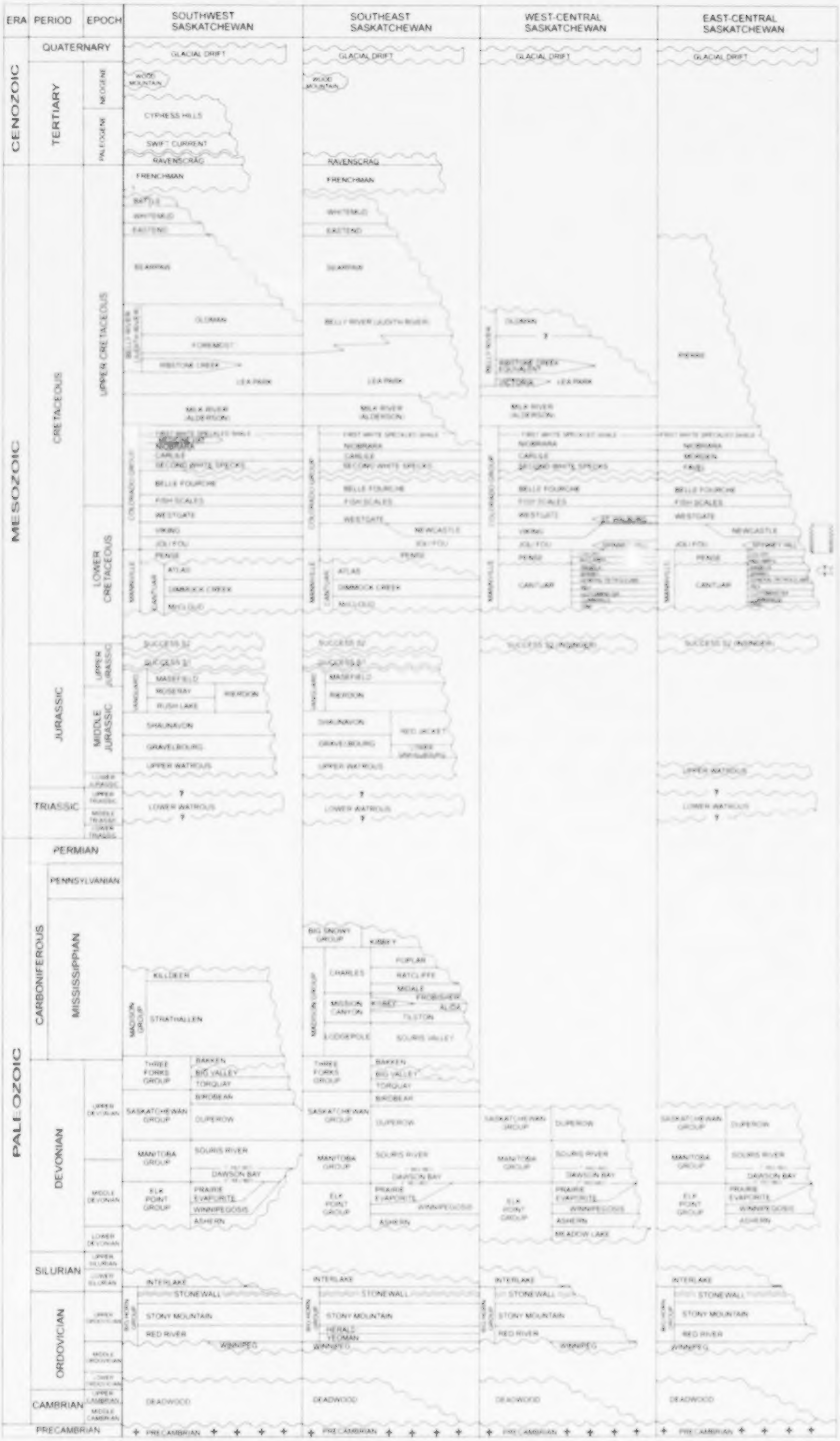


Figure 15 – Stratigraphic correlation chart of Saskatchewan (see also colour stratigraphic chart, back pocket). Note that the province is subdivided into four geographic areas, separated by common boundaries along latitude 52°N and longitude 106°W.

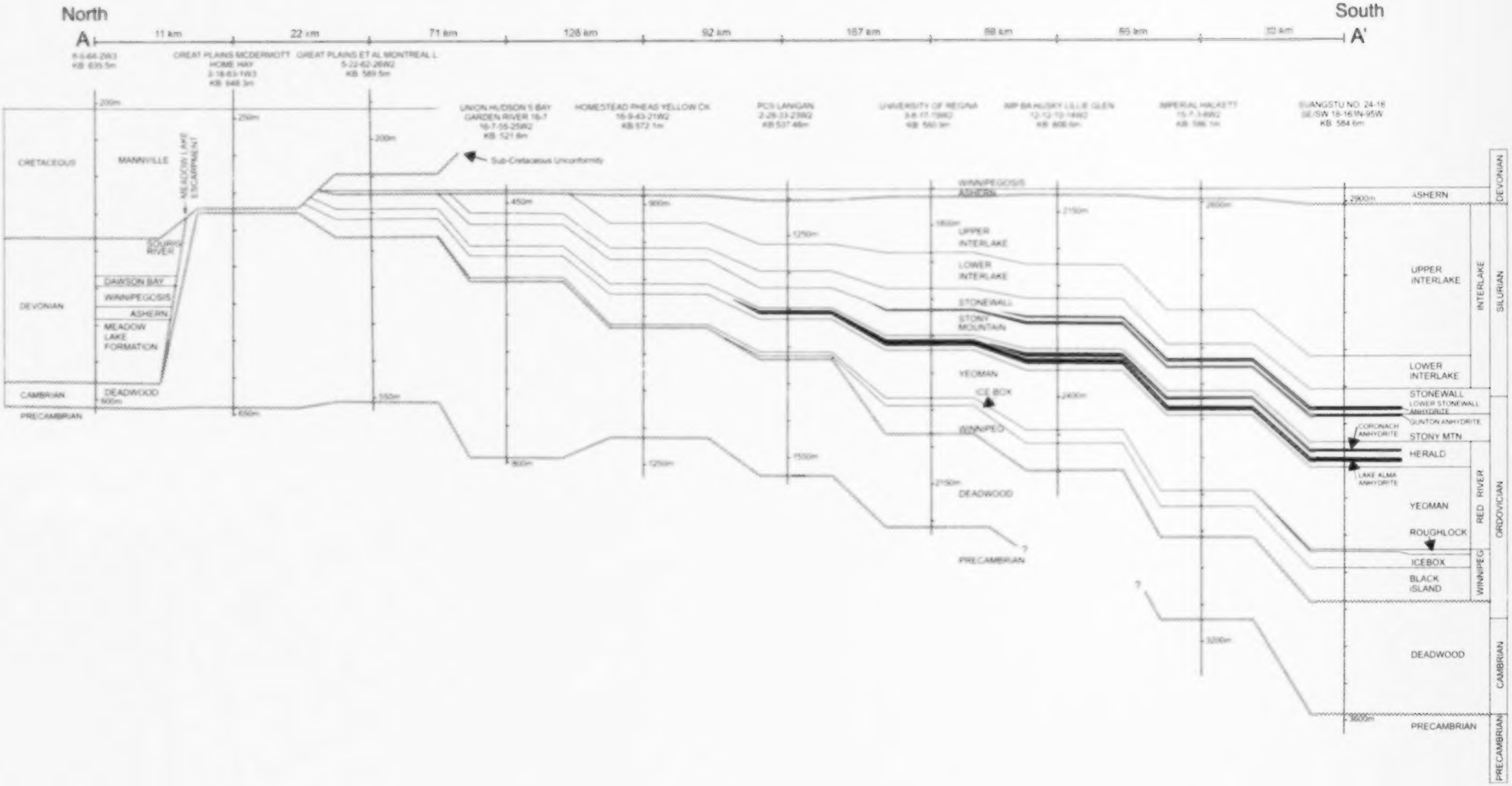
120 km north of the Meadow Lake Escarpment (MLE), the Deadwood is completely eroded and Lower Devonian rocks directly overlie the Precambrian surface. The Deadwood thickens westward toward its depocentre in southern Alberta, reaching more than 500 m at the Alberta-Saskatchewan boundary. It thins to an erosional zero edge in eastern Saskatchewan, north of latitude 50°N (Figure 17). Localized areas of zero or anomalously thin Deadwood strata in southern Saskatchewan coincide with Precambrian highs (Figure 17). They reflect topographic relief on the Precambrian surface during Deadwood deposition and/or uplift and subsequent erosion prior to deposition of the Winnipeg Formation (Kreis and Kent, 2000; Kreis, 2000a). The contact between the Deadwood and Winnipeg clastic units represents a continent-wide hiatus.

Distribution of the Winnipeg Formation reflects the earliest phase of subsidence of the Williston Basin, which had its depocentre in North Dakota. Maximum thickness of the Winnipeg Formation in Saskatchewan is 68 m near the Saskatchewan–North Dakota border (Figure 17). The contact between the Winnipeg and the overlying Yeoman Formation is interpreted as disconformable by some authors (e.g., Paterson, 1971; Kendall, 1976) and conformable by others (e.g., Vigrass, 1971).

Overlying the basal clastics are Ordovician and lowermost Silurian rocks, comprising the Red River (Yeoman and Herald formations) and the Stony Mountain, Stonewall and Lower Interlake formations (Figures 15, 16). They are characterized by a repetition of carbonate and evaporite units that include 1) widespread argillaceous marker beds; 2) fossiliferous, burrowed wackestones and lime mudstones; 3) fossiliferous and/or coated-grain wackestones-packstones-grainstones; 4) thin-bedded to laminated lime mudstones; and 5) laminated and nodular anhydrites (Kendall, 1976; Norford *et al.*, 1994; Haidl *et al.*, 1997). Dolomitization of carbonate beds is common and is an important factor in the distribution and quality of hydrocarbon-producing strata in the Red River. Evaporites are basin centred, with the oldest (Lake Alma anhydrite, Herald Formation) being the most widespread; anhydrites in the lower Interlake Formation are present in only a few areas in southeastern Saskatchewan and in the basin centre in North Dakota (Figure 16; Kendall, 1976; Magathan, 1987; Kreis and Haidl, 2000; Kreis and Haidl, in press a, b, c). Evaporites are absent and argillaceous marker beds are rare in the upper Interlake Formation, which is composed of 1) a lower sequence dominated by dolomudstones, with interbeds of skeletal-peloidal dolowackestones and dolopackstones, and lesser coral-stromatoporoid doloboundstones and dolofloatstones (Haidl, 1987); and 2) an upper sequence of dolostones, characterized by brecciated textures, erosional surfaces, fenestral fabrics and abundant dolomite cements that are interpreted as products of periodic subaerial exposure and vadose diagenesis (Haidl, 1987; Magathan, 1987). Ordovician and Silurian strata attain a maximum thickness of 438 m in southeastern Saskatchewan, near the depocentre of the Williston Basin in North Dakota (Figure 18). The Ordovician-Silurian boundary lies within the Stonewall Formation and is associated with the upper 't' argillaceous marker bed. Conodont data indicate that the time gap between deposition of the uppermost Ordovician strata and the earliest Silurian unit is approximately 3 to 5 m.y. (Nowlan and Haidl, 1999; Norford *et al.*, 1998).

Following a period of nondeposition and erosion during the Late Silurian and beginning of the Early Devonian, Early Devonian seas transgressed from the northwest as far south as the MLE (Figure 17), resulting in deposition of evaporites, carbonates and clastics of the Meadow Lake Formation (Figures 15, 16). Later transgression southward across the MLE resulted in an expansion of the Elk Point Basin into the Williston Basin area. Deposition of the argillaceous dolostones and dolomitic shales of the Ashern Formation was followed by that of platform carbonates, pinnacle reefs, large carbonate banks and interreef-bank organic-rich laminites with biogenic clasts (Winnipegosis Formation). Development of the Presqu'ile barrier reef complex to the northwest and a fall in relative sea level resulted in isolation of the Elk Point Basin from the open ocean. This, combined with evaporative drawdown and subsequent fluctuations in sea level, provided the environment in which vertically stacked sequences of laminated carbonate and anhydrite (e.g., Ratner Member, Winnipegosis Formation [Reinson and Wardlaw, 1972]; Ratner Formation [Jin and Bergman, 2001]), and the anhydrite, halite and potash of the Prairie Evaporite were deposited.

The Dawson Bay Formation and the Davidson Member of the Souris River Formation record two additional Middle Devonian major transgressive-regressive sequences (Figure 19). Similar carbonate-evaporite shallowing and/or shoaling-upward sequences characterize Upper Devonian strata represented by the upper Souris River Formation, and the Duperow and Birdbear formations (Figure 19). Rock types in these sequences include 1) argillaceous units, including the Second and First Red Beds; 2) nonfossiliferous carbonates; 3) fossiliferous carbonates (fossils include ostracodes, stromatoporoids, corals, brachiopods and crinoids); and 4) anhydrite and/or halite. Further work is required to facilitate the interpretation of this complex rock sequence. One example of the complexity is illustrated by evidence of an unconformity at the top of the Second Red Beds, which suggests that these strata, and perhaps also the First Red Beds, do not represent initial transgressive deposits but rather are genetically linked to the underlying regressive cycle (Dunn, 1982).


North
A
South
A'
11 km
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71 km
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167 km
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KB 848.3m
GREAT PLAINS ET AL MONTREAL L
5-22-62-26W2
KB 589.5m
UNION HUDSON'S BAY
GARDEN RIVER 16-7
16-7-55-25W2
KB 521.8m
HOMESTEAD PHEAS YELLOW CK
16-9-43-21W2
KB 572.1m
PCS LANIGAN
2-28-33-23W2
KB 537.48m
UNIVERSITY OF REGINA
KB 560.9m
IMP BA HUSKY LILLIE GLEN
IMPERIAL HALKETT
SUANGSTU NO. 24-18
SE/SW 18-161N-95W
KB 584.6m
Sub-Cretaceous Unconformity
MEADOW LAKE ESCARPMENT
CRETACEOUS
MANNVILLE
DEVONIAN
SOURIS RIVER
DAWSON BAY
WINNIPEGOSIS
ASHERN
MEADOW LAKE FORMATION
CAMBRIAN
DEADWOOD
PRECAMBRIAN
200m
250m
600m
650m
450m
800m
900m
1250m
1550m
1850m
2150m
2400m
2600m
2900m
3200m
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UPPER INTERLAKE
LOWER INTERLAKE
STONEWALL
STONY MOUNTAIN
YEOMAN
ICE BOX
WINNIPEG
DEADWOOD
PRECAMBRIAN
?
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LOWER STONEWALL ANHYDRITE
GUNTON ANHYDRITE
CORONACH ANHYDRITE
STONY MTN
HERALD
LAKE ALMA ANHYDRITE
ROUGHLOCK
ICEBOX
BLACK ISLAND
INTERLAKE
RED RIVER
SILURIAN
ORDOVICIAN

Figure 16 – Regional north-south stratigraphic cross-section A-A' through Phanerozoic strata (modified from Kreis and Haidl, in press d). Distribution of Winnipeg to Interlake rocks largely reflects depositional thickening toward the centre of the Williston Basin in North Dakota, and erosion associated with the sub-Devonian and sub-Cretaceous unconformities. North of the Meadow Lake Escarpment, which coincides with the erosional zero edge of Red River strata, pre-Devonian erosion resulted in formation of the Meadow Lake sub-basin, in which Lower Devonian rocks are preserved. Datum is top of the Ashern south of Township 62 and top of the Mannville for the most northerly wells. Location of the cross-section is shown in Figure 17.

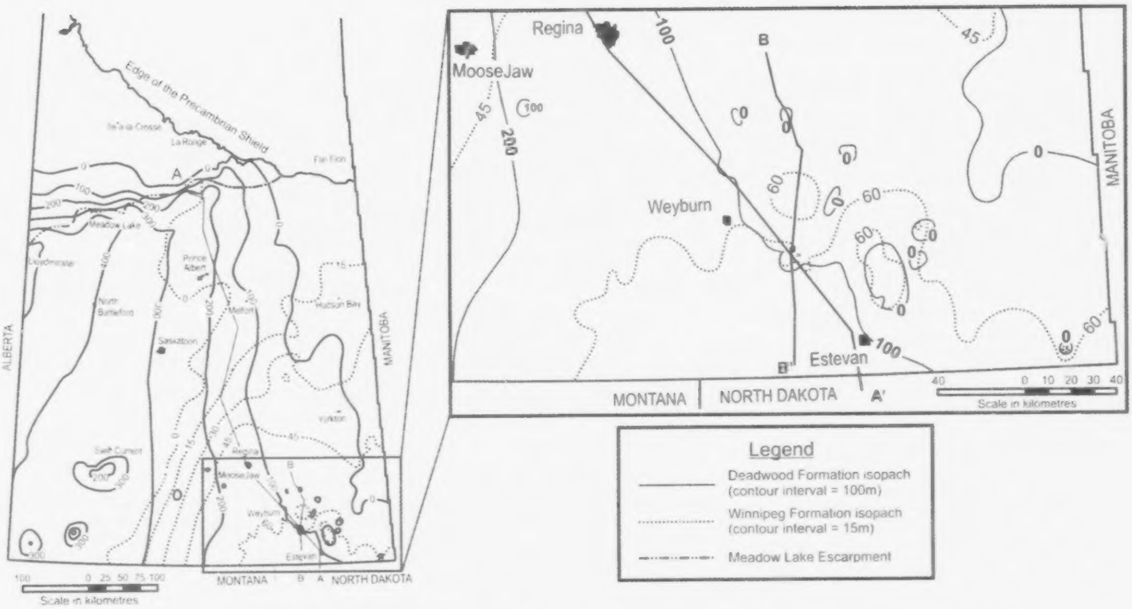

Edge of the Precambrian Shield
Île-à-la-Crosse
La Ronge
Flin Flon
A
Meadow Lake
Lloydminster
Prince Albert
North Battleford
Saskatoon
Melfort
Hudson Bay
Yorkton
Swift Current
Moose Jaw
Regina
Weyburn
Estevan
ALBERTA
MANITOBA
MONTANA
NORTH DAKOTA
B
A
Scale in kilometres
100 0 25 50 75 100
Regina
MooseJaw
Weyburn
Estevan
B
B'
A'
MANITOBA
MONTANA
NORTH DAKOTA
0 10 20 30 40
Scale in kilometres
Legend
Deadwood Formation isopach (contour interval = 100m)
Winnipeg Formation isopach (contour interval = 15m)
Meadow Lake Escarpment

Figure 17 – Isopach map of Cambro-Ordovician clastic rocks, including the Deadwood (solid lines; contour interval 100 m) and Winnipeg (dashed lines; contour interval 15 m) formations. In southern Saskatchewan, isolated areas of zero or anomalously thin Deadwood strata coincide with Precambrian highs. Note that, in the vicinity of the closed 100 m contour southeast of Moose Jaw, the Deadwood thins from 200 to 22 m (Kreis, 2000a; Kreis and Kent, 2000). Cross-section A-A' is shown in Figure 16 and cross-section B-B' in Figure 19.

Strata of the Three Forks Group encompass the uppermost Devonian and the transition to the Mississippian (Figures 15, 19). The Torquay Formation, composed of dolostone, shale and anhydrite, overlies the Birdbear Formation and is interpreted as a stacked series of tidal-flat deposits with abundant exposure surfaces (Halbertsma, 1994; Christopher, 1961). The Big Valley Formation unconformably overlies the Torquay and is dominated by marine shales and mudstones; a thin (less than 5 m thick) limestone bed is present at the top of the Big Valley in western Saskatchewan (Christopher, 1961). The overlying Bakken Formation is composed of black shales and a medial sandstone unit, within which lies the Mississippian-Devonian boundary. The maximum thickness of Devonian rocks, excluding the Bakken, is greater than 720 m (Figure 20). Salt dissolution, particularly within the Prairie Evaporite, has influenced present-day distribution of Devonian and younger strata; for example, evaporite units are locally thinned and overlying strata show depositional thickening in areas of local subsidence controlled by dissolution (Figure 19).

Above the clastic units that mark the transition from the Devonian to the Mississippian are carbonate-evaporite strata of the Mississippian Madison Group. The Mississippian succession generally represents a prograding, shallowing-upward megacycle that contains repeated, smaller, high- and low-energy, shallowing-upward cycles (Kent, 1984). In southeastern Saskatchewan, argillaceous or arenaceous carbonate strata delineate seven units termed 'Beds' (Fuzesy, 1960). In ascending order, these are the Souris Valley Beds, Tilston Beds, Frobisher Beds, Alida Beds, Midale Beds, Ratcliffe Beds and Poplar Beds (Figures 15, 21), although not all are regionally recognizable. Many of these units contain economically significant amounts of hydrocarbons. Mississippian strata (including the Bakken) thicken from their semicircular subcrop edge southward to more than 500 m at the Canada–United States border (Figure 22).

The Souris Valley Beds were deposited in settings ranging from basinal to upper shelf slope. In the basinal to lower shelf slope environments, Waulsortian-type bioherms (mudmounds) appear to have formed on Devonian paleohighs that resulted from multistage dissolution of Middle Devonian salt (Sereda, 1990). Upper slope deposits reflect storm processes acting upon a shallow carbonate ramp. The overlying Mississippian 'Beds' are dominantly shallow ramp or shelf carbonates that show repeated shallowing-upward or brining-upward cycles, which are often capped by evaporite deposits. Dolomitization is common and may have significant influence on reservoir quality.

Common facies observed in these beds include calcareous mudstones, crinoidal bioclastic carbonates, mixed bioclastic carbonates, oolitic carbonates and anhydrite with rare halite (Figure 21). The crinoidal bioclastic fa-

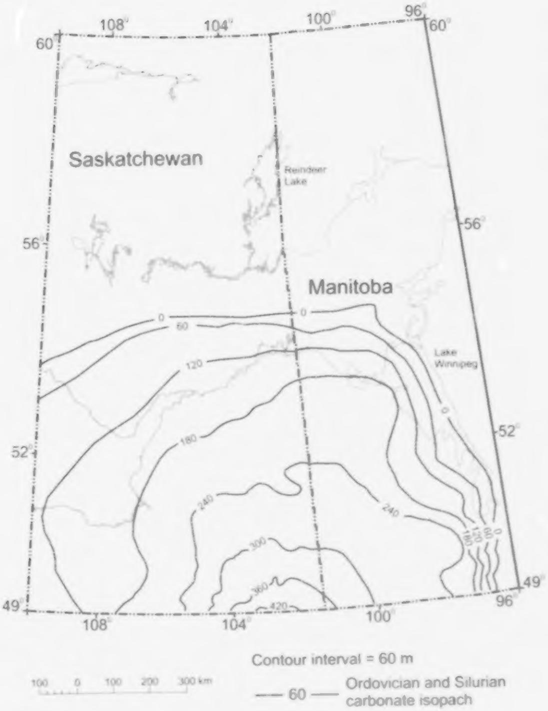


Figure 18 – Isopach map of Ordovician and Silurian carbonates (Yeoman and Herald formations [Red River], and Stony Mountain, Stonewall and Interlake formations) in Saskatchewan and Manitoba (contour interval 60 m).

cies contains more abundant crinoid fragments than the mixed bioclastic facies, but both also contain brachiopods, corals and bryozoans that form skeletal calcareous sands cemented by sparry calcite or organic debris in a micritic matrix. The oolitic or pseudo-oolitic facies includes oolites, pellets and pisolites, and appears to become coarser eastward (Kent, 1974). Organic debris associated with this facies is generally restricted to crinoids, foraminifera, ostracodes and gastropods. Evaporites are massive or nodular to banded. They may incorporate anhydrite, halite, penecontemporaneous dolomite, and coarse- and fine-grained red clastic rock. The clastic rocks predominate toward the top of the sequence. Thus, like the Devonian, the closing stage of Mississippian sedimentation is marked by clastic deposits, which probably reflect gradual emergence of the region. A major unconformity, representing uplift of the Precambrian Shield to the north, terminates the Paleozoic succession.

Mesozoic

Triassic-Jurassic

Terrestrial, red argillaceous quartzose sandstone and quartzose sandy and anhydritic mudstone, succeeded by marine anhydrite, dolostone and dolomitic limestone, lie with angular unconformity upon the eroded Paleozoic surface. These beds lap onto the erosional surface concentrically outward from the centre of the Williston Basin in North Dakota. Because the Watrous Formation and the lower member of the Gravelbourg Formation, representative of these deposits, blanket a karst-trellis topography, their combined thickness ranges from less than 30 m on the cuestas to more than 180 m in the valleys and sinks. The red beds are generally well indurated and anhydrite plugged. They therefore form an effective seal to some of the major unconformity-capped oil reservoirs in the underlying Mississippian strata. Nevertheless, permeable zones, most of which are genetically related to microfaulting, have developed locally, enabling oil to migrate upward into the Watrous, Gravelbourg and Shaunavon formations, and the Mannville Group, and to accumulate in a few small pools in the southeast (e.g., Manor, Wapella, Moosomin and Red Jacket pools).

Jurassic

The dominantly medium green-grey to dark grey, fossiliferous marine shales that make up the upper Gravelbourg Formation, the Shaunavon Formation and the Vanguard Group thicken to more than 270 m in south-central Saskatchewan, downdip from their eroded margin. The grey beds represent the continuation of the red-bed transgressive sequence and thus overlap the latter in the extreme southwest. Their erosional subcrop, however, lies basinward of the older deposits. Several thin, but economically important, tongues break the lithological homogeneity: 1) the Lower and Upper members of the Shaunavon Formation, and 2) the Roseray Formation of the Vanguard Group. The 10 to 30 m thick Lower Member of the Shaunavon Formation is characterized by cream-coloured lithographic limestone, marked by an upper 6 m of oolite in the west and a basal introduction of dark grey shale beds eastward. In the west, the Upper Member is made up of permeable calcareous sandstones. Toward Manitoba, Lower Shaunavon limestone yields to interbedded green-grey to olive grey and locally variegated shale and medium grey, fine-grained, muscovite-rich quartzose sandstone, whereas the Upper Shaunavon calcareous sandstones yield to lenticular quartzose sandstones, oolite, bioclastic arenite and rudite, dolostone and shale. Here, lithofacies mapping has led to redefinition of the Shaunavon and the upper Gravelbourg, which are collectively recognized as the Red Jacket Formation (Kreis, 1991).

The Roseray Formation is composed of well-sorted, fine-grained, weakly cemented and very permeable sandstone with an argillaceous matrix, and argillaceous interbeds making up less than 10% of the succession in the north and about 40% in the south (Christopher, 1974). White kaolinitic sandstone yields southward to dark grey glauconitic shale. The formation is 15 to 46 m thick over an area of 26 000 km^2 and projects

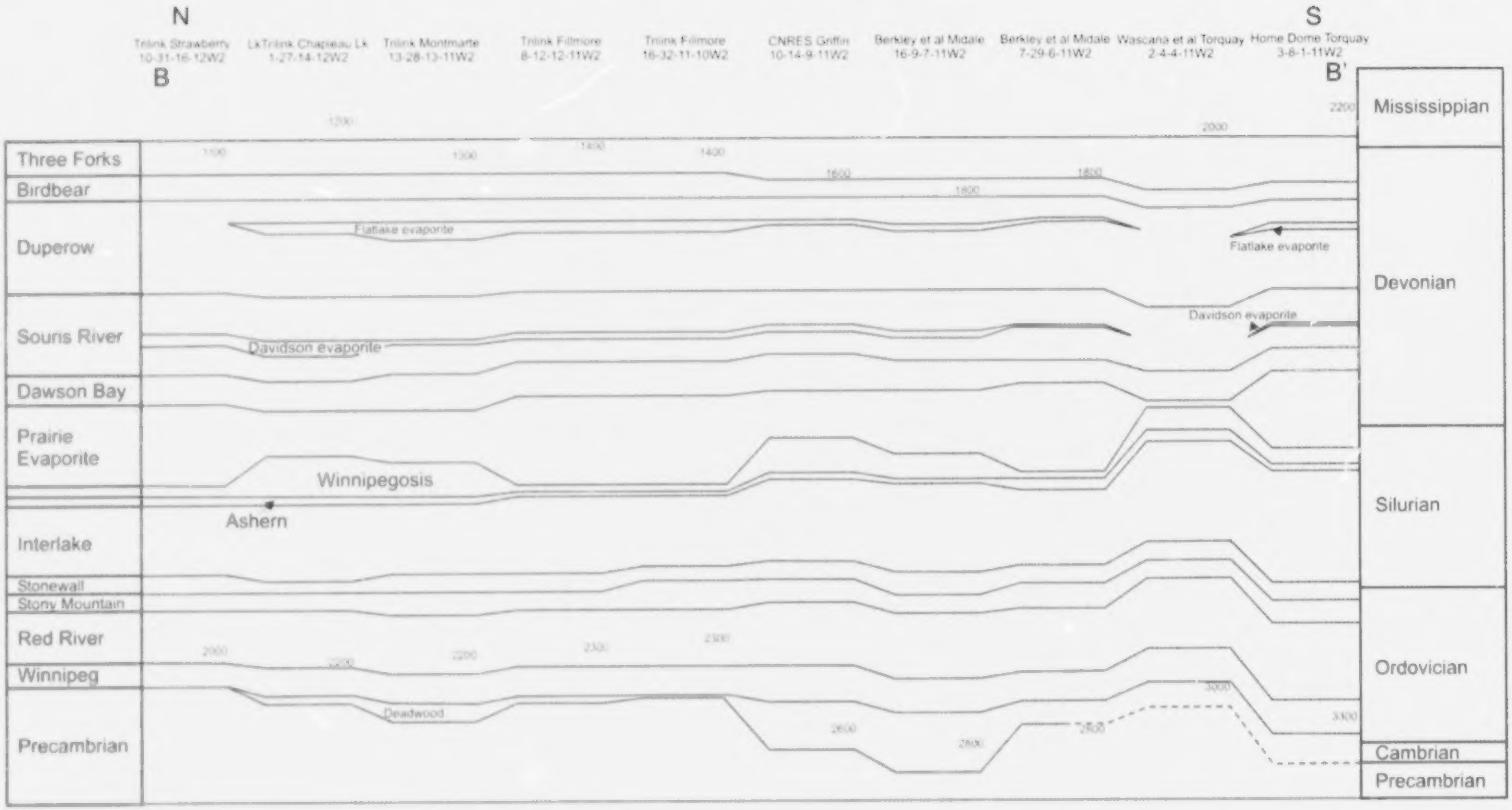

N
S
B
B'
Trilink Strawberry 10-31-16-12W2
LkTrilink Chapeau Lk 1-27-14-12W2
Trilink Montmartre 13-28-13-11W2
Trilink Fillmore 8-12-12-11W2
Trilink Fillmore 16-32-11-10W2
CNRES Griffin 10-14-9-11W2
Berkley et al Midale 16-9-7-11W2
Berkley et al Midale 7-29-6-11W2
Wascana et al Torquay 2-4-4-11W2
Home Dome Torquay 3-8-1-11W2
Three Forks
Birdbear
Duperow
Souris River
Dawson Bay
Prairie Evaporite
Interlake
Stonewall
Stony Mountain
Red River
Winnipeg
Precambrian
Mississippian
Devonian
Silurian
Ordovician
Cambrian
Precambrian
Flatlake evaporite
Flatlake evaporite
Davidson evaporite
Davidson evaporite
Winnipegosis
Ashern
Deadwood
1200
1100
1300
1400
1400
1600
1800
1800
2000
2200
2000
2200
2200
2300
2300
2600
2800
2800
3000
3300

Figure 19 – North-south stratigraphic cross-section through Devonian and older strata in southeastern Saskatchewan. Evaporite units having thick halite beds are shown on this section; anhydrite and thin halite beds have not been differentiated. Note the relationships between distribution of the Prairie Evaporite, and older and younger strata (e.g., in Wascana et al Torquay 2-4-4-11W2). Distribution of Deadwood strata reflects the fact that many new wells (on this section), drilled on seismic anomalies, are associated with Precambrian structural highs, where the Deadwood is thin or absent. Datum is top of the Bakken Formation of the Three Forks Group. Depths are in metres.

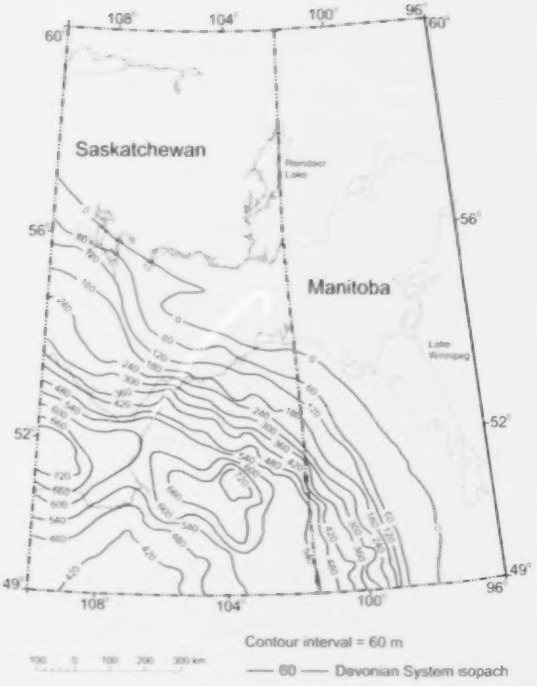

108°
104°
100°
96°
60°
56°
52°
49°
Saskatchewan
Manitoba
Reindeer Lake
Lake Winnipeg
Contour interval = 60 m
60 Devonian System isopach
100 0 100 200 300 km

Figure 20 – Isopach map of Devonian strata in Saskatchewan and Manitoba (contour interval 60 m).

southward from the sub-Cretaceous unconformity as a broad tongue between longitudes 108°W and 104°W, to taper across the Canada–United States border as thin, lenticular argillaceous sandstones.

Jurassic isopachs, like those for Mississippian strata but unlike those for the Devonian (Figure 22), are restricted to the southern third of the province and are concentric on the structural Williston Basin. This concentricity reflects a post-Appalachian orogenic control exercised by the basin and contrasts with the more northwesterly shelf-like interbasin distribution of Devonian deposits.

Jura-Cretaceous

Five main, noncontiguous regions of unconformity-bounded Jura-Cretaceous strata (Success Formation) are present in Saskatchewan (Christopher, 2003). The Success Formation consists of white and light grey, kaolin-indurated quartzose sandstones, siltstones and mudstones, with abundant feldspar, sphaerosiderite, chert, coal and carbonaceous fragments, and, in the south, glauconite. Thickness ranges up to 75 m (Christopher, 1974, 1984, 2003). The southernmost bodies (Success S1 and S2) form northward extensions of similar bodies in Montana and North Dakota, and generally overlie the Upper Jurassic Vanguard Group. In the Kindersley area, north of the Jurassic erosional edge, the 'Detrital' beds overlie rocks of the Madison Group or Bakken Formation. The 'Insinger' beds overlie Jura-Triassic and Mississippian strata in southeastern Saskatchewan, and Upper Devonian rocks in central Saskatchewan.

Cretaceous

The sandstones and shales of the Mannville Group drape over southward-dipping strata that range in age from Upper Jurassic in the extreme south to as old as Cambrian along the northern edge of the Phanerozoic rocks. These deposits inlay a topography that was highest in southwestern Saskatchewan, whence valleys radi-

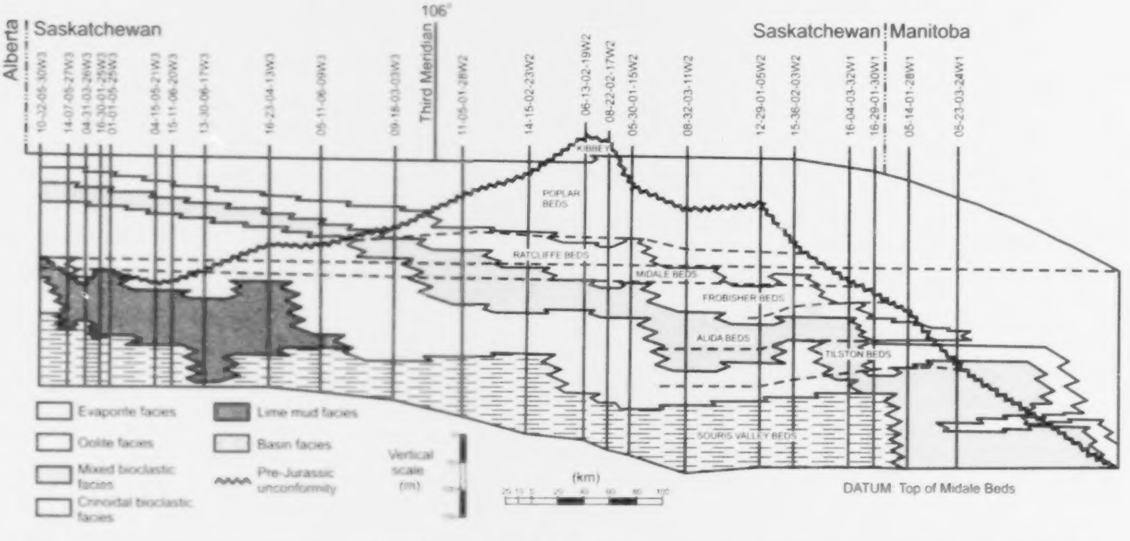

Alberta
Saskatchewan
106°
Third Meridian
Saskatchewan
Manitoba
10-32-05-30W3
14-07-05-27W3
04-31-03-26W3
16-30-01-25W3
01-01-05-25W3
04-15-05-21W3
15-11-06-20W3
13-30-06-17W3
16-23-04-13W3
05-11-06-09W3
09-18-03-03W3
11-05-01-28W2
14-15-02-23W2
06-13-02-19W2
08-22-02-17W2
05-30-01-15W2
08-32-03-11W2
12-29-01-05W2
15-36-02-03W2
16-04-03-32W1
16-29-01-30W1
05-14-01-28W1
05-23-03-24W1
KIBBEY
POPLAR BEDS
RATCLIFFE BEDS
MIDALE BEDS
FROBISHER BEDS
ALIDA BEDS
TILSTON BEDS
SOURIS VALLEY BEDS
Evaporite facies
Oolite facies
Mixed bioclastic facies
Crinoidal bioclastic facies
Lime mud facies
Basin facies
Pre-Jurassic unconformity
Vertical scale (m)
(km)
20 10 0 20 40 60 80 100
DATUM: Top of Midale Beds

Figure 21 – East-west diagrammatic stratigraphic cross-section of the Mississippian in Saskatchewan and Manitoba (after Kent, 1974).

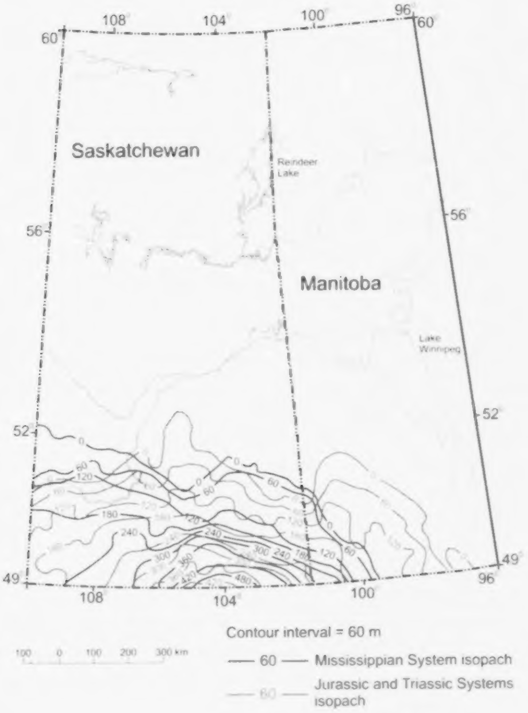

108°
104°
100°
96°
60°
56°
52°
49°
Saskatchewan
Manitoba
Reindeer Lake
Lake Winnipeg
Contour interval = 60 m
100 0 100 200 300 km
— 60 — Mississippian System isopach
— 60 — Jurassic and Triassic Systems isopach

Figure 22 – Isopach map of the Mississippian System (solid lines) and the Jurassic and Triassic systems (grey lines) in Saskatchewan and Manitoba (contour interval 60 m).

ated to the north, northeast and east across Jurassic and Mississippian strata and turned north and northwest across the Devonian in eastern and central Saskatchewan (Christopher, 2003). Consequently, the thickness of the group ranges from less than 30 m to more than 100 m locally and to 260 m regionally (Figure 23).

Sedimentary rocks are variably kaolinitic, chloritic and illitic crossbedded sandstone, ranging from white and olive green to dark grey in colour, and dark and medium grey sandy mudstone with carbonaceous and coaly beds. Marine indicators are conspicuous in the central part of the province, and at certain horizons in the extreme south where fluviatile elements are otherwise dominant (Christopher, 1984, 1974, 2003).

The Colorado Group (Albian-Santonian age) consists of predominantly massive black shales with subordinate sandstone bodies tonguing into Saskatchewan from the Rocky Mountain foreland in the west and from the Precambrian Shield in the north and east. It thickens fairly uniformly from about 100 m at its eastern outcrop edge (Pasquia Hills area) to 500 m in the southwest corner of the province. The base of the Fish Scales Formation, a widespread and readily recognizable marker unit, is taken as the boundary between the Upper and Lower Cretaceous.

Shales are dominant in total thickness, but the group is stratigraphically delineated by sandstone and calcareous units. Thus, the Viking Formation of burrowed, poorly sorted and pebbly sandstone separates the black shale of the basal Joli Fou Formation from that of the Westgate Formation. The Viking thins from 54 m in the southwest to 12 m toward the north, and shales out eastward. Close to the Manitoba border, shallow marine and shoreline muddy sandstones and siltstones of the Newcastle Formation appear to be stratigraphically younger than the Viking (Koziol, 1988). Subordinate sandstones in the Joli Fou Formation (Spinney Hill sandstone) and in the Westgate Formation (St. Walburg sandstone) tongue-in from the north. In the Fort à la Corne area of central Saskatchewan, diamond-bearing kimberlites have been discovered within Lower Cretaceous strata of the upper Mannville Group and Lower Colorado Group (Joli Fou and Westgate formations). Calcareous shaly units serve to vertically delimit the upper part of the Colorado Group. For example, progressing upward in east-central Saskatchewan, the calcareous Favel Formation (Turonian) is overlain by the noncalcareous Morden Formation (Turonian-Coniacian), which in turn is succeeded by the calcareous Niobrara Formation. Although sandstones are a minor component of the Colorado, those in the southwest in the Belle Fourche (the lower and upper Belle Fourche

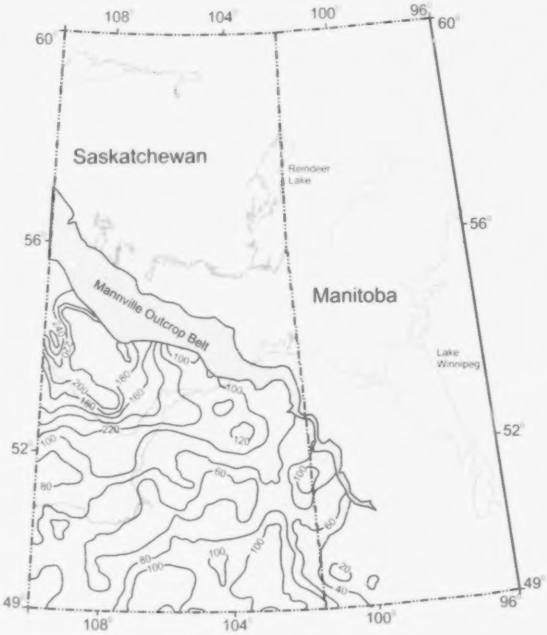

108°
104°
100°
96°
60°
56°
52°
49°
Saskatchewan
Manitoba
Reindeer Lake
Lake Winnipeg
Mannville Outcrop Belt
Contour interval = 20 m
100 0 100 200 300 km
— 60 — Mannville isopach

Figure 23 – Isopach map of Mannville Group in Saskatchewan and Manitoba (contour interval 20 m; modified from Christopher, 2003).

sandstones, commonly named the Second White Speckled sandstones in earlier literature) and Niobrara formations (the Medicine Hat sandstone) host large natural-gas fields in Saskatchewan (Gilboy, 1988; Ridgley *et al.*, 2001; Ridgley and Gilboy, 2001).

The Alderson Member of the Lea Park Formation, commonly named the 'Milk River Formation' by geologists working in Saskatchewan, is made up of grey, fine- to medium-grained, muddy marine sandstones with intercalated siltstones, and dark grey silty shales (Ridgley, 2000; Payenberg, 2002). It is by far the most productive natural-gas reservoir rock in the province. The Alderson is transgressively overlapped by the marine shales of the upper Lea Park. The intertonguing of shoreface, fluviomarine and continental sandstones and siltstones (Belly River and Eastend) with marine shales (Lea Park and Bearpaw) results in stratigraphic nomenclature problems in many areas. The Eastend Formation, less than 30 m thick, is succeeded by up to 22 m of white to light grey shale, siltstone and sandstone (Whitemud Formation) and 7.5 m of dark grey bentonitic shale (Battle Formation), followed disconformably by 60 m of medium-grained sandstone, bentonitic shale and muddy siltstone (Frenchman Formation), all of which are predominantly continental in origin. Exposures of the Frenchman Formation in southwestern Saskatchewan have yielded dinosaur remains, including a well-preserved skeleton of a *Tyrannosaurus rex*.

Cenozoic

The distribution of Tertiary strata in southern Saskatchewan is illustrated in Figure 24. Light grey sandstones, siltstones and silty mudstones with interbedded coal characterize the 160 to 240 m thick Ravenscrag Formation (Paleocene), which rests conformably on the Frenchman Formation in the Cypress Hills and Wood Mountain–Missouri Coteau areas. The Cretaceous-Tertiary boundary is placed at the contact between the Frenchman and Ravenscrag, and is marked by high iridium values at the base of a coal seam at several locations in southern Saskatchewan (Dawson *et al.*, 1994). The Ravenscrag is unconformably overlain by more than 170 m of conglomerate and interbedded sandstone of the Cypress Hills Formation (Oligocene). Locally, Upper Eocene conglomerate and sandstone (Swift Current Formation) and Miocene sand and gravel (Wood Mountain Formation), up to 15 m thick, cap the Ravenscrag Formation.

Quaternary

Much of Saskatchewan's present-day landscape is the result of geological events and processes during the Quaternary Period. The Quaternary, which is subdivided into the Pleistocene and Holocene epochs, is the youngest geological time period. Beginning approximately 2 million years ago, this time period is characterized by marked climatic changes, glaciations and associated processes. The Pleistocene is defined as the age of glaciation. In North America, at least four glacial stages, separated by interglacial intervals when the climate was similar to or warmer than today, have been recognized during the Pleistocene. Multiple ice advances and retreats occurred within each stage. From oldest to youngest, the stages are the Nebraskan, Kansan, Illinoian, and Wisconsinan. The Holocene, or Recent epoch, is the postglacial time interval in which we live today, beginning approximately 10 000 years ago after the final retreat of the glaciers.

Glaciation

Christiansen (1968b, 1992) and Barendregt *et al.* (1998) have identified at least eight glacial advances and retreats in southern Saskatchewan during the middle to late Pleistocene (Figure 25). The terminus for these continental ice masses commonly extended south of the border into the United States (Dyke and Prest, 1987a, b). Only portions of the Cypress Hills and Wood Mountain have been untouched by glaciation. These upland plateau areas preserve the Late Tertiary landscape.

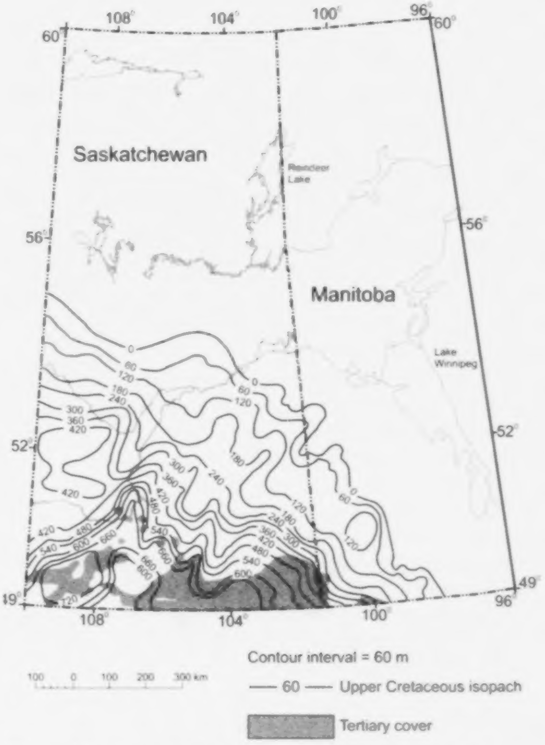


Figure 24 – Isopach map of Upper Cretaceous strata in Saskatchewan and Manitoba (contour interval 60 m). Also shown is the distribution of Tertiary rocks.

During the Late Wisconsinan, at least three ice sheets developed in separate regions of Canada: the Cordilleran, Laurentide and Innutian. The largest was the Laurentide ice sheet, which covered much of interior Canada, including Saskatchewan. Ice flow across the province was generally to the south-southwest, as the ice advanced from a dispersal centre located in the Keewatin region of Nunavut. In southern Saskatchewan, the south-southwest-flowing lobe came in contact with east-flowing ice from Alberta, whereas the westerly flow from the Hudson Bay lobe advanced into eastern Saskatchewan from Manitoba (Figure 26). It is important to note that some of features, such as those that indicate a southeast flow across the province from Cold Lake to Esterhazy, may be relicts of earlier glaciations.

Saskatchewan can be divided into two broad physiographic regions, based on its bedrock geology. In the north, the hard, predominantly crystalline rocks of the Precambrian Shield, with its southern fringe of Paleozoic carbonate rocks, contrast sharply with the soft sedimentary rocks of the Phanerozoic Basin that underlie the Interior Plains of the Prairies. The difference in competency of the bedrock in these two regions resulted in markedly different effects on the flow dynamics of the overriding glacial ice, thus producing distinctly different landscapes. In general, the Precambrian-Paleozoic terrain was predominantly a zone of erosion. The resistance of the hard substrate resulted in patchy drift cover and an abundance of glacially scoured and moulded bedrock outcrops. The till generally consists of a silty sand matrix with abundant clasts. The exception is over the Athabasca Basin, where glacial erosion of the less resistant sandstone resulted in an increased sediment load in the ice. Consequently, the glacial drift cover is much more extensive and thicker over the Basin than the rest of the Shield region.

The Interior Plains is primarily a region of glacial deposition. As the ice moved off the more resistant Shield unsaturated with debris, it encountered the soft Cretaceous shales and quickly became saturated with the shale over a short distance. The pancake stacking of successive till units, the consistent lithology of the tills, and the thickness of the deposits all suggest that the erosive powers of the ice were greatly reduced in this region. In general, the older tills are rich in shale, whereas the younger tills are sandier and more carbonate rich (Christiansen, 1968b, 1992). Schreiner (1990) proposed that the existing till sequence in southern Saskatchewan was a result of progressive stripping of the Cretaceous shales from the Shield contact region, exposing the carbonate rocks by successive ice advances.

Quaternary Stratigraphy

The Quaternary stratigraphy of Saskatchewan in Figure 25 was developed by Christiansen (1968b, 1992), based on the thick, laterally continuous glacial sequences present in southern Saskatchewan. Quaternary sediments (glacial drift) in southern Saskatchewan are commonly 100 to 200 m thick, but can range in thickness from zero (e.g., Wood Mountain) to more than 300 m in the Touchwood Hills (Millard *et al.*, 1989). In contrast, glacial drift in the north is generally less than 20 m thick. Multiple till units within thicker drift are found only in protected areas such as bedrock depressions. The stratigraphic framework has not been applied in northern regions due to the paucity of preserved sequences and their lack of lateral continuity.

The Pleistocene glacial, proglacial and nonglacial drift, consisting of till and intertill stratified sediments, has been subdivided into the Empress, Sutherland and Saskatoon groups. The Empress Group includes both Tertiary and Pleistocene stratified sediments that lie between the bedrock and lowermost till unit (Whitaker

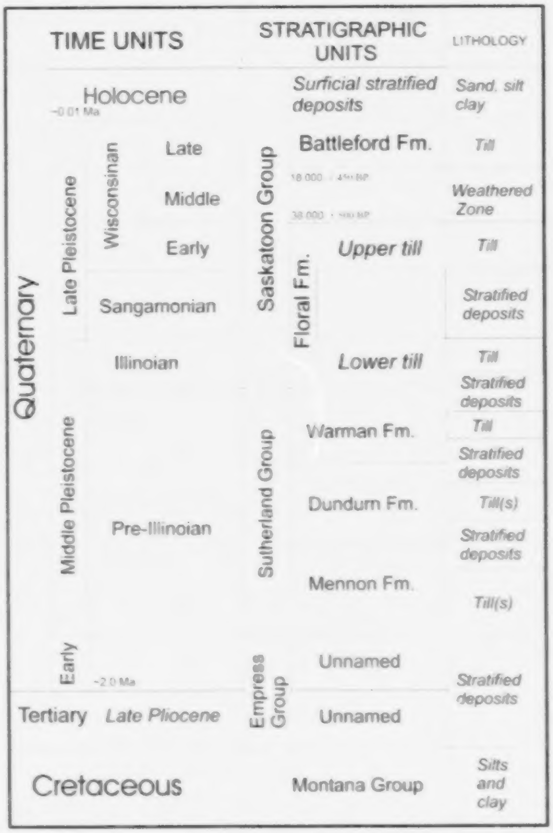

TIME UNITS
STRATIGRAPHIC UNITS
LITHOLOGY
Holocene
~0.01 Ma
Surficial stratified deposits
Sand, silt clay
Quaternary
Late Pleistocene
Wisconsinan
Late
Middle
Early
Saskatoon Group
Battleford Fm.
Till
18 000
38 000
Weathered Zone
Floral Fm.
Upper till
Till
Sangamonian
Stratified deposits
Illinoian
Lower till
Till
Stratified deposits
Middle Pleistocene
Pre-Illinoian
Sutherland Group
Warman Fm.
Till
Stratified deposits
Dundurn Fm.
Till(s)
Stratified deposits
Mennon Fm.
Till(s)
Early
~2.0 Ma
Empress Group
Unnamed
Stratified deposits
Tertiary
Late Pliocene
Unnamed
Cretaceous
Montana Group
Silts and clay

Figure 25 – Quaternary stratigraphic chart and related lithological units, Saskatoon area (after Christiansen, 1992; Barendregt* et al.*, 1998).

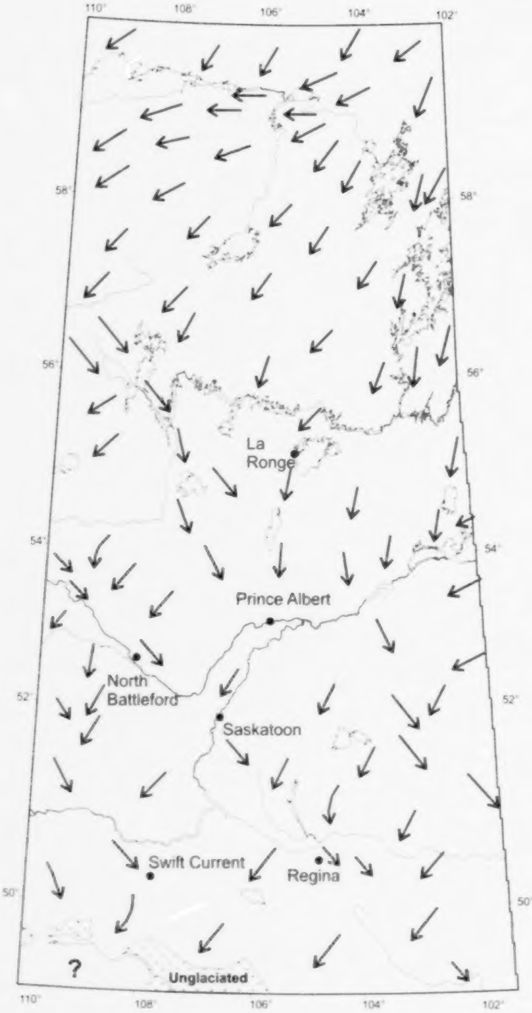


Figure 26 – General ice-flow directions, based on glacial landforms (Dyke and Prest, 1987b; Klassen, 1989). The last Late Wisconsinan glacial advance across the province was to the southwest. The ice-flow directions displayed likely record multiple glaciations.

and Christiansen, 1972). The Sutherland Group is further subdivided into the Mennon, Dundurn and Warman formations (Figure 25). To date, these older glacial and interglacial sediments have not been identified as Kansan or Nebraskan. The overlying Saskatoon Group consists of the Floral and Battleford formations, capped by Holocene 'surficial stratified deposits'. Christiansen (1968b, 1992) and others (Schreiner, 1990; Christiansen *et al.*, 1995; Barendregt *et al.*, 1998) have provided more detailed descriptions of the stratigraphic units. Klassen (1989) provided a Quaternary lithostratigraphic correlation chart for the three Prairie Provinces.

Deglaciation

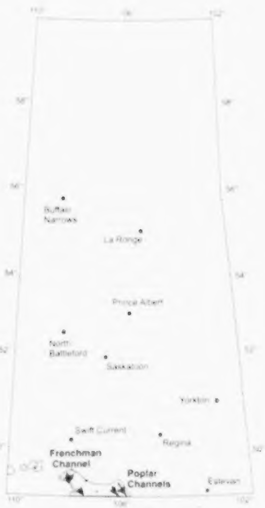
Although multiple ice sheets have advanced and retreated over Saskatchewan, the present-day landscape is primarily a result of the last major glacial event during the Late Wisconsinan. The Late Wisconsinan ice sheet reached its maximum extent just south of the Saskatchewan–United States border around 20 000 to 23 000 ^{14}C BP (noncalibrated radiocarbon years before present; Dyke and Prest, 1987a, b; Klassen, 1989). With the exception of the Cypress Hills and Wood Mountain areas, all of Saskatchewan was covered by ice (Figures 26, 27).

The final deglaciation of Saskatchewan is believed to have begun around 17 000 to 18 000 ^{14}C BP, with the province being essentially ice free around 8500 to 8000 ^{14}C BP (Christiansen, 1979; Schreiner, 1984; Dyke and Prest, 1987b; Klassen, 1989). The series of diagrams in Figure 27, a compilation of current models, illustrates the Late Wisconsinan deglaciation history of the province. Reconstruction of the deglaciation history and identification of successive ice-frontal positions have been derived from the location of proglacial lakes and their outlets (spillways), ice-marginal meltwater drainage channels, glacial landforms (e.g., end moraines, ice-thrust moraines) and radiocarbon dates (Christiansen, 1979; Schreiner, 1984; Dyke and Prest, 1987b; Dyke and Dredge, 1989; Klassen, 1989, 1992, 1994, 2002; Fisher and Smith, 1994; Christiansen *et al.*, 1995; Morlan *et al.*, 2001; Teller 2001).

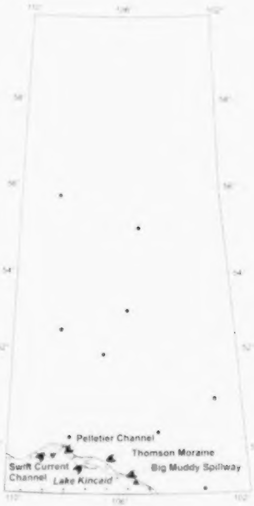
Glacial Landforms and Deposits

Glacial sediments can be subdivided into two distinctive but gradational groups: 1) till, laid down directly by the ice; and 2) stratified sediments, deposited in water either by glaciofluvial or glaciolacustrine processes. Glaciofluvial stratified sediments (sand and gravel) are further subdivided into ice-contact stratified drift, deposited beneath or immediately in front of the ice, and outwash sediments, deposited by meltwater streams beyond the glacier. Glaciolacustrine sands and silts were deposited in glacial lake deltas, whereas the finer silts and clays settled offshore in the lake basins. The surficial geology of southern Saskatchewan (Simpson, 1997) is shown on the *Geological Highway Map of Saskatchewan* provided in the back pocket.

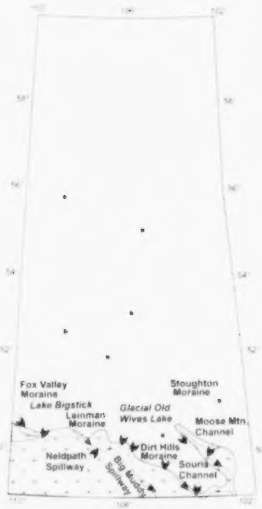
In northern Saskatchewan, the rugged terrain consists primarily of glacially modified bedrock outcrops with a discontinuous cover of glacial sediments. Erosional features created by the advancing ice dominate the northern landscape. The regional structural trends of the Precambrian Shield are oriented in a northeast-southwest direction, roughly parallel to ice flow. Glacial scouring has deepened and emphasized these bedrock features. Most outcrops of hard rock exhibit evidence of glacial scouring and polishing that record


Buffalo Narrows
La Ronge
Prince Albert
North Battleford
Saskatoon
Yorkton
Swift Current
Regina
Frenchman Channel
Poplar Channels
Estevan
110°
106°
102°
58°
56°
54°
52°
50°

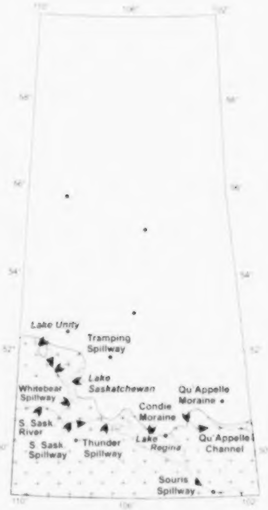
18 ka BP


Pelletier Channel
Thomson Moraine
Swift Current Channel
Lake Kincaid
Big Muddy Spillway
110°
106°
102°

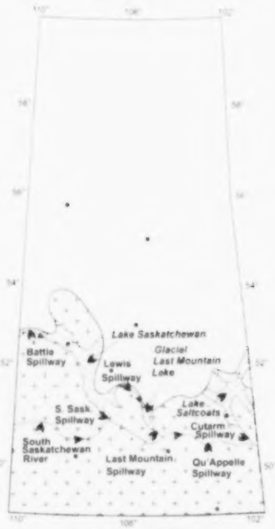
14 ka BP


Fox Valley Moraine
Lake Bigstick
Leinman Moraine
Glacial Old Wives Lake
Stoughton Moraine
Moose Mtn. Channel
Neidpath Spillway
Big Muddy Spillway
Dirt Hills Moraine
Souris Channel
110°
106°
102°

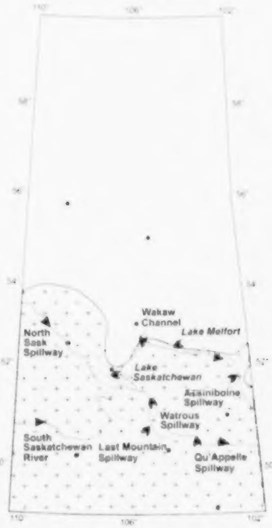
13 ka BP


Lake Unity
Tramping Spillway
Lake Saskatchewan
Whitebear Spillway
Qu'Appelle Moraine
Condie Moraine
S. Sask River
S. Sask Spillway
Thunder Spillway
Lake Regina
Qu'Appelle Channel
Souris Spillway
110°
106°
102°

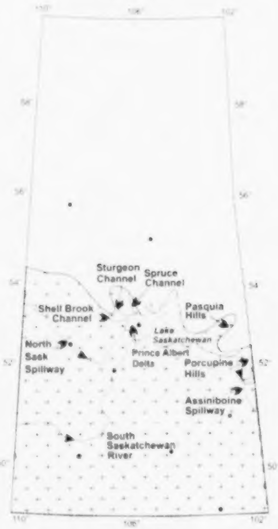
12 ka BP


Lake Saskatchewan
Battle Spillway
Lewis Spillway
Glacial Last Mountain Lake
S. Sask Spillway
Lake Saltcoats
Cutarm Spillway
South Saskatchewan River
Last Mountain Spillway
Qu'Appelle Spillway
110°
106°
102°

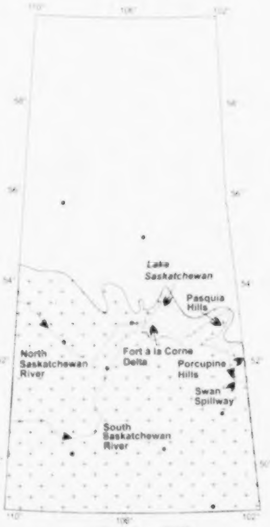
~11.5 ka BP


Wakaw Channel
Lake Melfort
North Sask Spillway
Lake Saskatchewan
Assiniboine Spillway
Watrous Spillway
South Saskatchewan River
Last Mountain Spillway
Qu'Appelle Spillway
110°
106°
102°

~11.2 ka BP


Sturgeon Channel
Spruce Channel
Shell Brook Channel
Pasquia Hills
Lake Saskatchewan
North Sask Spillway
Prince Albert Delta
Porcupine Hills
Assiniboine Spillway
South Saskatchewan River
110°
106°
102°

~11 ka BP


Lake Saskatchewan
Pasquia Hills
North Saskatchewan River
Fort à la Corne Delta
Porcupine Hills
Swan Spillway
South Saskatchewan River
110°
106°
102°

10.5 ka BP

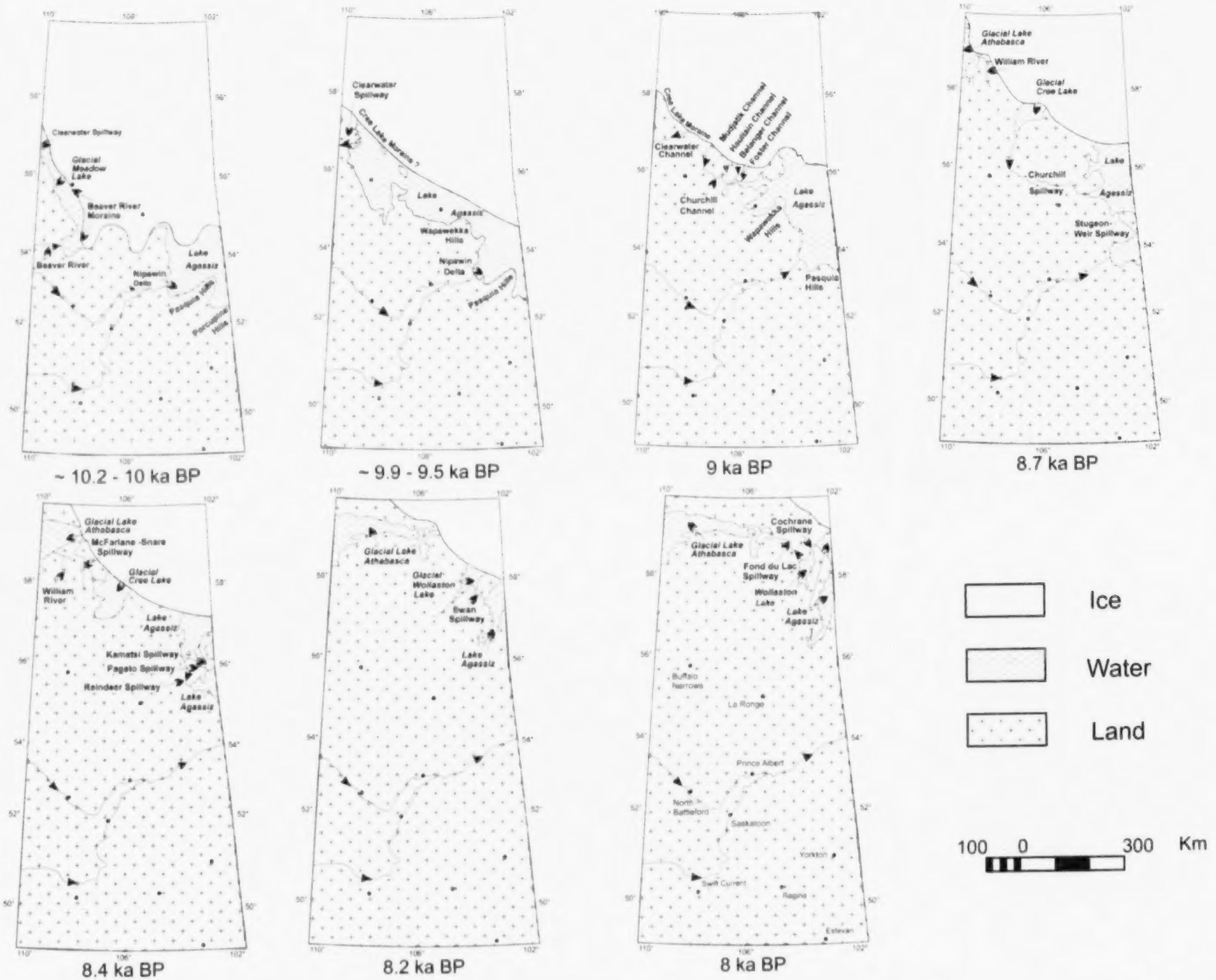

~ 10.2 - 10 ka BP
Clearwater Spillway
Glacial Meadow Lake
Beaver River Moraine
Beaver River
Nipawin Delta
Lake Agassiz
Pasquia Hills
Porcupine Hills
~ 9.9 - 9.5 ka BP
Clearwater Spillway
Cree Lake Moraine ?
Lake Agassiz
Wapawekka Hills
Nipawin Delta
Pasquia Hills
9 ka BP
Cree Lake Moraine
Clearwater Channel
Mudjatik Channel
Haultain Channel
Belanger Channel
Foster Channel
Churchill Channel
Lake Agassiz
Wapawekka Hills
Pasquia Hills
8.7 ka BP
Glacial Lake Athabasca
William River
Glacial Cree Lake
Churchill Spillway
Lake Agassiz
Stugeon-Weir Spillway
8.4 ka BP
Glacial Lake Athabasca
McFarlane-Snare Spillway
Glacial Cree Lake
William River
Lake Agassiz
Kamatsi Spillway
Pagato Spillway
Reindeer Spillway
Lake Agassiz
8.2 ka BP
Glacial Lake Athabasca
Glacial Wollaston Lake
Swan Spillway
Lake Agassiz
8 ka BP
Cochrane Spillway
Glacial Lake Athabasca
Fond du Lac Spillway
Wollaston Lake
Lake Agassiz
Buffalo Narrows
La Ronge
Prince Albert
North Battleford
Saskatoon
Yorkton
Swift Current
Regina
Estevan
Ice
Water
Land
100
0
300
Km
110°
106°
102°
58°
56°
54°
52°
50°

Figure 27 – Late Wisconsinan deglaciation history of Saskatchewan (compiled and modified from Christiansen, 1979; Schreiner, 1984; Dyke and Prest, 1987b; Klassen, 1989, 1992, 1994, 2002; Fisher and Smith, 1994; Christiansen et al., 1995; Teller, 2001). *The ages of the phases have been extrapolated from published data only (~ indicates approximate or best fit). Refer to referenced papers for radiocarbon dates.*

the direction of ice flow. Outcrops have been shaped into roches moutonnées and whaleback ridges, aligned in the direction of ice flow. Bedrock surfaces are commonly polished and etched with striae, grooves and chatter marks. Regional ice-flow directions are also recorded by streamlined depositional landforms, such as drumlins, fluted ground moraine and crag-and-tail features. The spectacular drumlin fields of the Athabasca Basin are some of the most extensive in the world.

Most of the prominent glacial depositional landforms in northern Saskatchewan were created during retreat of the ice sheet. Hummocky and ridged moraine, ice-contact eskers and kames, sandy proglacial outwash plains and, to lesser extent, glacial-lake deposits are all common. The most extensive outwash deposits occur over the Athabasca Basin. Eskers, which are believed to have formed during the waning stage of the ice sheet, are generally oriented parallel to regional ice flow. Numerous extensive esker systems cross the Precambrian Shield region. Some, such as the system that stretches along the Geikie River, have been traced for more than 100 km. In contrast, eskers are rare in southern Saskatchewan, generally occurring as short isolated ridges.

A prominent end moraine, known as the Cree Lake Moraine, can be traced more or less continuously across northern Saskatchewan from latitude 56°N at the Manitoba border to 58°N at the Alberta border. The Cree Lake moraine comprises several different landforms, ranging from a broad hummocky moraine with a series of interwoven ridges to a single esker-like ridge. This moraine marks a major stillstand of the ice front in northern Saskatchewan at approximately 9 000 to 10 000 ^{14}C BP (Schreiner, 1984; Dyke and Prest, 1987b).

The landscape south of the Shield is dominated by Quaternary glacial and postglacial landforms. Prominent glacial landforms found across the southern part of the province include undulating and hummocky ground moraine, ice-thrust moraines, ridged and hummocky end moraines, dead (stagnant)-ice moraines (e.g., Moose Mountain), kame complexes, fluted ground moraine (narrow, straight, parallel ridges and grooves) and, to a lesser extent, eskers and crevasse fillings.

Some of the more interesting landscape features of the Prairie region are the glaciotectonic landforms. The bedrock surface of the Phanerozoic Basin, composed of soft sediments, was further modified by deformation and thrusting (glaciotectonics) by the ice. Large blocks of bedrock and pre-existing glacial sediments were dislodged and stacked by the advancing ice into a series of parallel, arcuate ice-thrust ridges, such as the Dirt Hills, south-southwest of Regina. This ice-thrust moraine is 7.5 km wide, 120 m high and 40 km long (Christiansen and Sauer, 1997). Major depressions, such as the one at Fire Lake, west of Unity, are the result of excavation by glacial plucking (Christiansen and Sauer, 1988). These depressions often have associated hills composed of disturbed bedrock and till sequences that have been derived from the depression; the resulting landform is termed a 'hill-hole pair' (e.g., Red Deer Hill near Prince Albert; Christiansen and Sauer, 1993). Interestingly, the first confirmed diamondiferous kimberlite body in Saskatchewan, found at Sturgeon Lake, was actually a large ice-rafted block (approximately 110 m in diameter). Another large block was found a few kilometres to the northwest, but the source of these blocks has yet to be found.

As the ice retreated toward the northeast, large volumes of meltwater drained from the ice sheet through large channels carved by the meltwater (e.g., Frenchman River, Big Muddy channel and Arm River) or ponded along the ice margin to form large glacial lakes (e.g., lakes Regina, Saskatchewan and Agassiz). Extensive clay-silt plains (e.g., Regina), sandy deltaic areas, and relict shorelines of raised beaches and wave-cut benches are present-day remnants of these lakes. The glacial lakes were drained by spillways or outlet channels (e.g., Last Mountain Lake, Qu'Appelle, South Saskatchewan and Souris spillways). Misfit streams now occupy many of these large, steep-sided valleys.

Lake Agassiz was the most extensive and long lived of the glacial lakes in Saskatchewan (11 000 to 8 000 ^{14}C BP). As the ice retreated, the north shore of Lake Agassiz advanced from the southeastern edge of the Shield northward over Reindeer Lake in northeastern Saskatchewan. At one point, Lake Agassiz extended from Reindeer Lake in northeastern Saskatchewan southeastward into Ontario and the northern United States. As a result, glaciolacustrine offshore clay-silt and strandline (e.g., beaches) deposits extend from the Nipawin area north across the southeastern Shield to north of Reindeer Lake. Many of the large lakes of northern Saskatchewan (e.g., Lake Athabasca, Cree Lake and Wollaston Lake) are remnants of large proglacial lakes that were relatively short lived.

Winds swept across exposed sand and silt deposits after the retreat of the glacial waters. Numerous postglacial eolian features were formed at this time, such as sand-blasted boulders (ventifacts), loess deposits (e.g., near Verlo) and extensive areas of sand dunes, such as the Great Sand Hills in southwestern Saskatchewan and the Athabasca Sand Dunes in the northwestern part of the province.

Bogs and fens, in which thick deposits of peat have accumulated since the retreat of the ice, cover extensive areas in northern Saskatchewan. Peat plateaus, palsen and thermokarst features occur where permafrost is present in the peat deposits. Such features are particularly common north of latitude 58°N.

Implications of Glacial and Postglacial Processes

The glacial and postglacial processes created many of the natural resources of Saskatchewan and have therefore had a profound impact on the provincial economy. For example, glaciofluvial sediments are important sources of sand and gravel for construction. Buried sand and gravel aquifers are important local and municipal water supplies. Approximately 40% of Saskatchewan's rural population relies on groundwater as their water source. Glacial deposits provide the parent material for the province's soils. The flat, clay-rich glacial lakebeds supply fertile soils and ideal terrain for agriculture. Isolated or trapped lake basins became the sites of the rich sodium-sulphate deposits of southern Saskatchewan.

The province's glacial landscape provides an abundance of recreational and tourism opportunities. Ecologically unique regions, such as the Great Sand Hills, Athabasca Sand Dunes, Frenchman River valley and Big Muddy badlands, are excellent ecotourism attractions. The large, deep valleys and their misfit streams, such as the Qu'Appelle River valley, provide ideal locations for recreational activities. Other popular localities, such as Duck Mountain, Moose Mountain, Churchill River and Prince Albert National Park, owe their existence to glaciation.

Particularly in northern Saskatchewan, the scouring action of the glaciers created glacial dispersion fans (i.e., mineralized boulders, till and kimberlite (diamond) indicator minerals) from subcropping mineralized sources. The mineral-exploration industry uses these mineralized dispersal fans to help locate unexposed mineral resources. The large, expansive bogs, particularly in the Beauval area, are excellent sources of peat.

Economic Geology

In October 1930, by virtue of the Natural Resources Transfer Agreement, all Crown lands, mines, minerals and royalties, except those on Indian Lands, were placed under the control of the province. Since that time, mineral and energy resources have been a cornerstone for the provincial economy. Today, nonrenewable resources, including petroleum, coal and metallic and industrial minerals, are Saskatchewan's most important industrial sector, providing 14.2% of the province's GDP in 2001, compared to about 8% for agriculture, and accounting for some 38% of the total value of provincial exports (Figure 28).

Saskatchewan is divided into a northern region of deformed Precambrian basement and undeformed Athabasca sedimentary rocks, and a southern region of sedimentary strata ranging from Cambrian to Tertiary in age. This separation determines the distribution of mineral-industry and related government activities: the metallic-mineral environment is in the northern half and the industrial minerals, as well as petroleum, natural gas and coal, are in the southern half.

The petroleum and coal industries are robust. Saskatchewan ranks second in Canada for inland oil reserves, behind only Alberta, and ranks third in production of both natural gas and coal, behind Alberta and British Columbia. The industry accounted for $4.4 billion[1], or 26%, of provincial exports in 2001 and $685 million, or 11%, of direct crown revenues. Enhanced recovery techniques have bolstered an industry that has managed to generally increase Saskatchewan's annual production over the past 10 years. Coal is currently the predominant power source for the province, accounting for some 55% of output. Coal-bed methane is a new focus for exploration and potential development, and CO_2 sequestration is being studied for enhanced recovery and environmental applications.

Mineral resources have been an important part of the Saskatchewan economy throughout the past century. Saskatchewan ranks third among the provinces in gross, nonfuel mineral production, which was valued at about $2.16 billion in 2001 and generated some $250 million in direct crown revenues. Saskatchewan produces 100% of Canada's uranium and 95% of the country's potash, and is preeminent on the world stage for both commodities, accounting for about 34% of world output in uranium and about 33% of world production, and 43% of world trade, in potash. The Athabasca Basin and the Prairie Evaporite are the world's premier districts for uranium

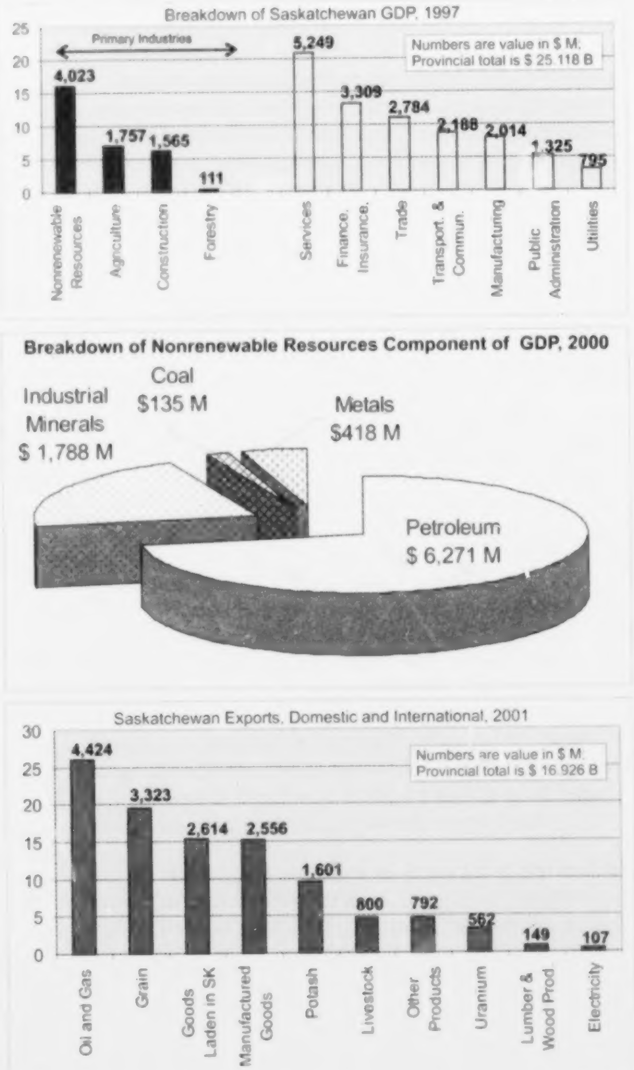


Figure 28 – Position of the Energy and Mines sector in the Saskatchewan economy: top) percentage breakdown of GDP by industry in 1997; middle) breakdown of the GDP contribution from nonrenewable resources in 2000; bottom) percentage breakdown of the value of provincial exports in 2001.

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[1] All values in this report are expressed in Canadian dollars unless otherwise indicated.

and potash exploration and mining, respectively, and current reserves will maintain Saskatchewan's world market share of these commodities for decades to come. Saskatchewan's diverse mineral endowment also includes diamonds at Fort à la Corne, a truly unique kimberlite field with tremendous economic potential. There is also significant potential for major discoveries in base metals, gold, platinum-group metals and rare-earth elements, and for significant new production of clay, silica sand, building stone and brines.

In 2000, the Canadian Institute of Mining and Metallurgy published a revised classification of reserves and resources, which became incorporated into the Canadian Securities Commission's National Instrument 43-101 to create an industry standard for the reporting of reserves and resources. The 'Geology, and Mineral and Petroleum Resources of Saskatchewan' report presents reserve and resource estimates derived from a variety of published and public record sources. Many of these sources predate establishment of NI 43-101, and no attempt has been made to recalculate those figures to the NI 43-101 standard. Likewise, post–NI 43-101 reserve and resource estimates have not been verified as complying with NI 43-101 standards.

Energy Resources

Saskatchewan ranks second among Canadian provinces in production of oil, and third in production of natural gas. Government revenue from oil and gas in the 2001-2002 fiscal year amounted to 76% of the total accruing from nonrenewable resources in the province. Of the approximately 75 000 boreholes drilled in the province until mid-2002 in search of oil, gas and potash, some 45 000 have produced, or are capable of producing, oil or gas. In the last decade, improved horizontal drilling and production technologies, discovery of large volumes of oil in deep reservoirs, and such regulatory changes as deep rights reversion and an enhanced royalty structure have all contributed to overall strong growth in oil production (Figure 29). Approximately 33% of Saskatchewan's crude oil is now produced from horizontal wells.

Saskatchewan ranks third among Canadian provinces in coal production, and coal has formed a consistent building block of the Saskatchewan economy for the entire century. Coal was mined in west-central Saskatchewan, near Kelfield, from the Cretaceous Judith River Formation in the 1930s, but current production is exclusively from the lignite-rank coals of the Tertiary Ravenscrag Formation, mined within about 100 km of the province's southern border. Production has been relatively constant at about 12 to 14 million tonnes (t) per year since the commissioning of the Shand power plant in 1992 (Figure 30); coal is currently the most important power source for the province, providing 55% of total output. Coal is widely distributed in the Cretaceous Mannville Group, with drill-indicated resources in the area south of La Ronge, west of Kerrobert and northwest of Kindersley. Although the Cretaceous coals are generally buried at depths that make economic conventional mining seem unlikely, these subbituminous coals may have potential as a source of coal-bed methane.

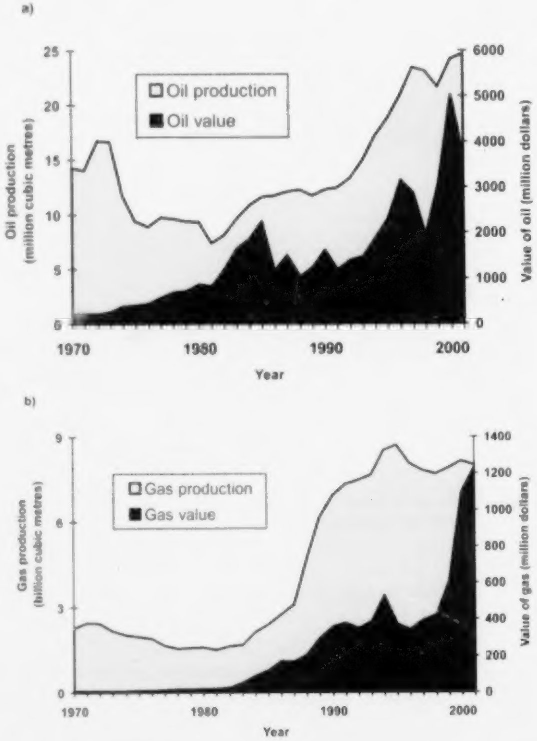


Figure 29 – Production volume and value, during the period 1970-2000, for Saskatchewan a) oil, and b) gas.

Petroleum

General Geology

For administrative purposes, the part of the province south of the Precambrian Shield edge is subdivided into four oil and natural-gas production and disposition areas, designated by Roman numerals I to IV (Figure 31). Oil is generally classified into one of four types — heavy, medium, light or condensate — based upon its chemical and flow characteristics. Historically, Saskatchewan has produced light, medium and heavy oils, but has recently begun to produce high-quality condensate oil. Area I, the most northerly of Saskatchewan's producing regions, produces heavy oil and shallow gas from reservoirs in the Lloydminster area. Area II, the Kindersley area, is noted for its heavy and light oils, and shallow gas production. Area III, the Swift Current area, covers southwestern Saskatchewan and produces medium oil and shallow gas. Area IV, the Estevan area, forms the southeastern part of the province, in which

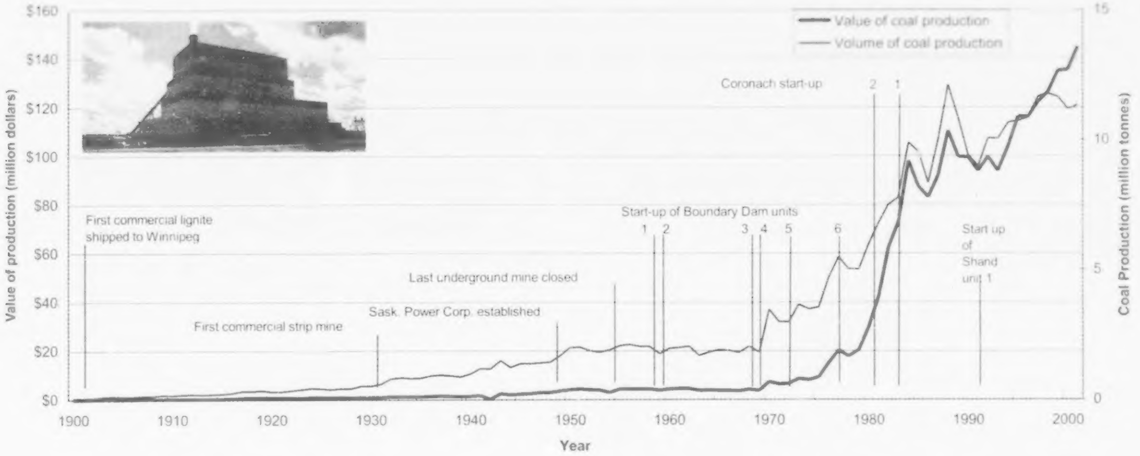


Figure 30 – Historical summary of lignite production and power development in Saskatchewan, 1900-2000. Inset photo shows coal-fired generating station at Poplar River.

light, medium and, recently, condensate oils are produced.

Much of the oil produced in Saskatchewan has migrated from source rocks in Alberta, Montana and North Dakota; lesser amounts have been generated from local source rocks. The oil is trapped in stratigraphic, structural and combination traps within carbonate (Figure 32) and clastic (Figure 33) reservoir rocks ranging in age from Ordovician to Cretaceous.

Most of Saskatchewan's natural gas is produced from shallow (275 to 760 m deep) clastic reservoirs that are Cretaceous in age (Figure 34). In the Swift Current area, large resources are found in laterally extensive, unconventional (continuous), biogenic gas reservoirs characterized by low permeability. In the Lloydminster area, Mannville gas is commonly trapped in structures related to dissolution of salts in the Prairie Evaporite. Stratigraphic trapping mechanisms are also important in the three producing areas.

Exploration and Development History

Conventional Drilling and Production

Records of drilling in Saskatchewan indicate that the first well was drilled by the Geological Survey of Canada (GSC) at Fort Pelly in 1874-1875 and the second at Fort Carleton in 1875. The wells reached depths of 153 and 53 m, respectively. Around 1883, the Canadian Pacific Railway made several "borings" at Grenfell, McLean and Belle Plaine to obtain water. In a letter written December 2, 1955 from Saskatchewan's Administrator of Petroleum Lands to the editor of the Canadian Oil and Gas Industries, the well at Belle Plaine was reported to have reached 473 m and to have encountered a "small gas flow," probably the first record of hydrocarbons in the province.

From 1900 to 1919, 14 wells were drilled and, from 1920 to 1929, 18 were drilled; all were unsuccessful. The Lloydminster Gas Company No. 1 well, however, spudded on November 22, 1933, encountered natural gas on January 9, 1934. This discovery led to the establishment of the Lloydminster Gas Pool, with initial reserves of 233 x 10^6 m^3. The pool is still producing from the Colony Sand of the Mannville Group (Cretaceous) at a depth of 518 m.

A total of 103 wells, including 11 successful gas wells, was drilled from 1930 to 1939. Areas explored included the Pasquia Hills region in the eastern half of Area I. Although oil was found in the Lloydminster area in 1935, it was not commercially viable.

Exploration and development grew substantially from 1940 to 1949, when 413 wells were drilled (109 of these in 1947). Two new gas pools were established in the Unity area (southwest corner of Area I), in a Mannville sandstone locally referred to as the 'Unity Sand' at 632 m in 1944 and in the Viking Sand (Cretaceous) at 503 m in 1945. The former is now depleted after producing some 267 x 10^6 m^3 of gas.

Commercial quantities of heavy (low-gravity) crude oil were discovered in the Lloydminster area, in 1943 in Alberta and in 1944 in Saskatchewan. Production was from the Mannville Sparky Sand. By the end of the decade, four oil pools had been established: Lone Rock, Dulwich and Marsden, all producing from the Sparky Sand; and Gully Lake, which produced from another Mannville sand, the Waseca. All four pools are still operational. Shallow gas was found in the mid-1940s in the Kamsack area of eastern Saskatchewan, but was not commercially viable.

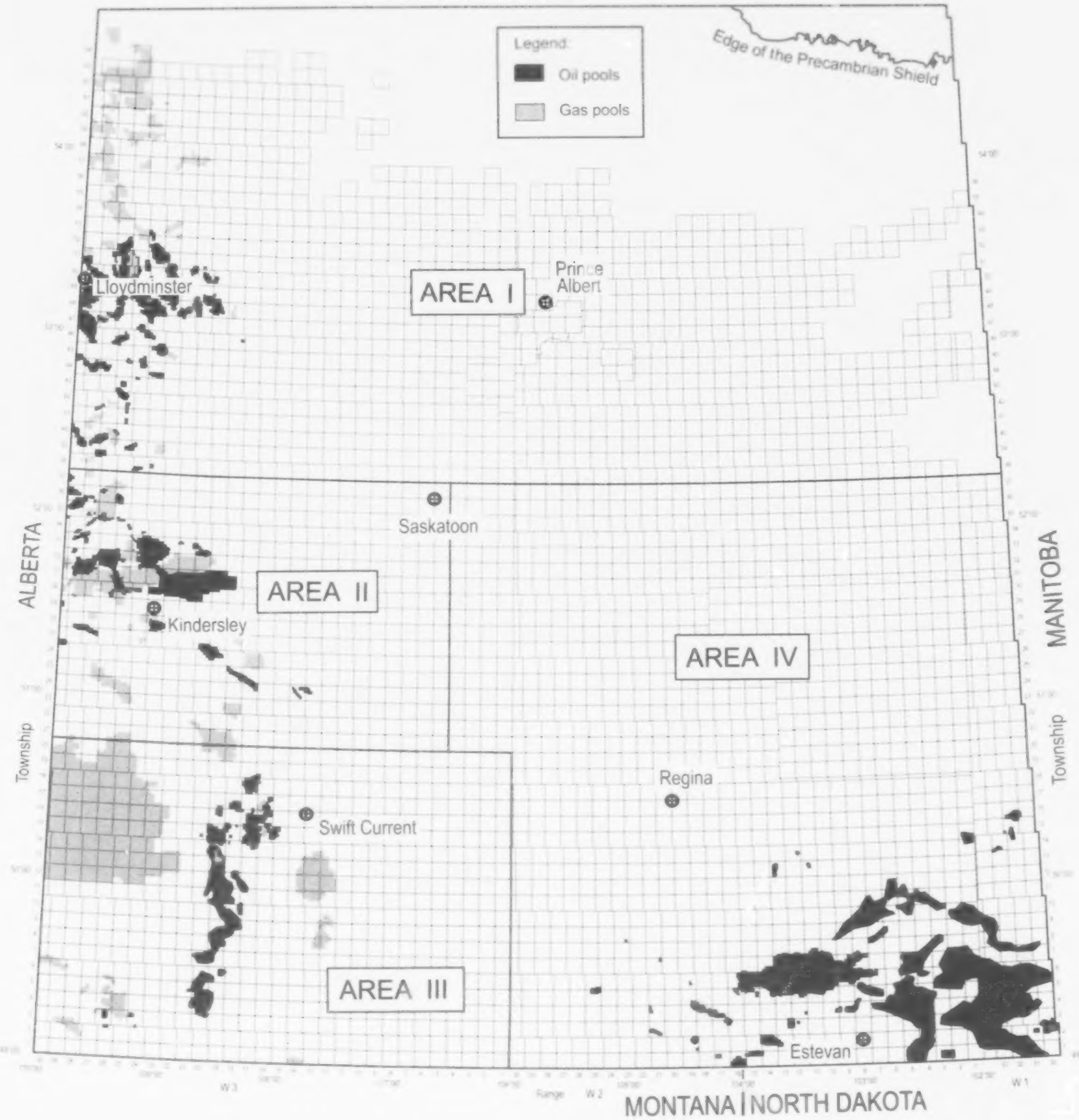

Legend:
Oil pools
Gas pools
Edge of the Precambrian Shield
AREA I
Lloydminster
Prince Albert
Saskatoon
AREA II
Kindersley
AREA IV
ALBERTA
MANITOBA
Township
Township
Regina
Swift Current
AREA III
Estevan
W 3
Range
W 2
W 1
MONTANA | NORTH DAKOTA

Figure 31 – Distribution of oil and gas pools and the four production and disposition areas (I-IV) in Saskatchewan.

From 1950 to 1959, drilling activity greatly increased, with 7114 wells being completed (1258 of these in 1957). Several of these wells resulted from exploration and development projects undertaken by the rapidly expanding potash industry (potash wells are included in future totals). Numerous finds of oil and gas were made, leading to the delineation of about 129 new pools. Ten of these exploited heavy-oil reservoirs in the Lloydminster area. More exciting for the province was the discovery of new types of oil and gas in new areas and at new stratigraphic levels. For example, in 1951, the Coleville Pool in the Kindersley area (Area II) began producing heavy crude from the Bakken Sand (Mississippian) at 823 m depth. With initial reserves of 12.0 x 10^6 m^3 of oil, it is still active and has recoverable reserves of some 2.8 x 10^6 m^3. Also in 1951, the Coleville-Smiley and Brock gas pools were discovered in the same area. They produced from the Viking Sand (Cretaceous) at approximately 700 m and were the forerunners of nine similar pools found before 1960.

In 1952, three new areas of hydrocarbon accumulations were discovered: 1) the southeast (Area IV), where the

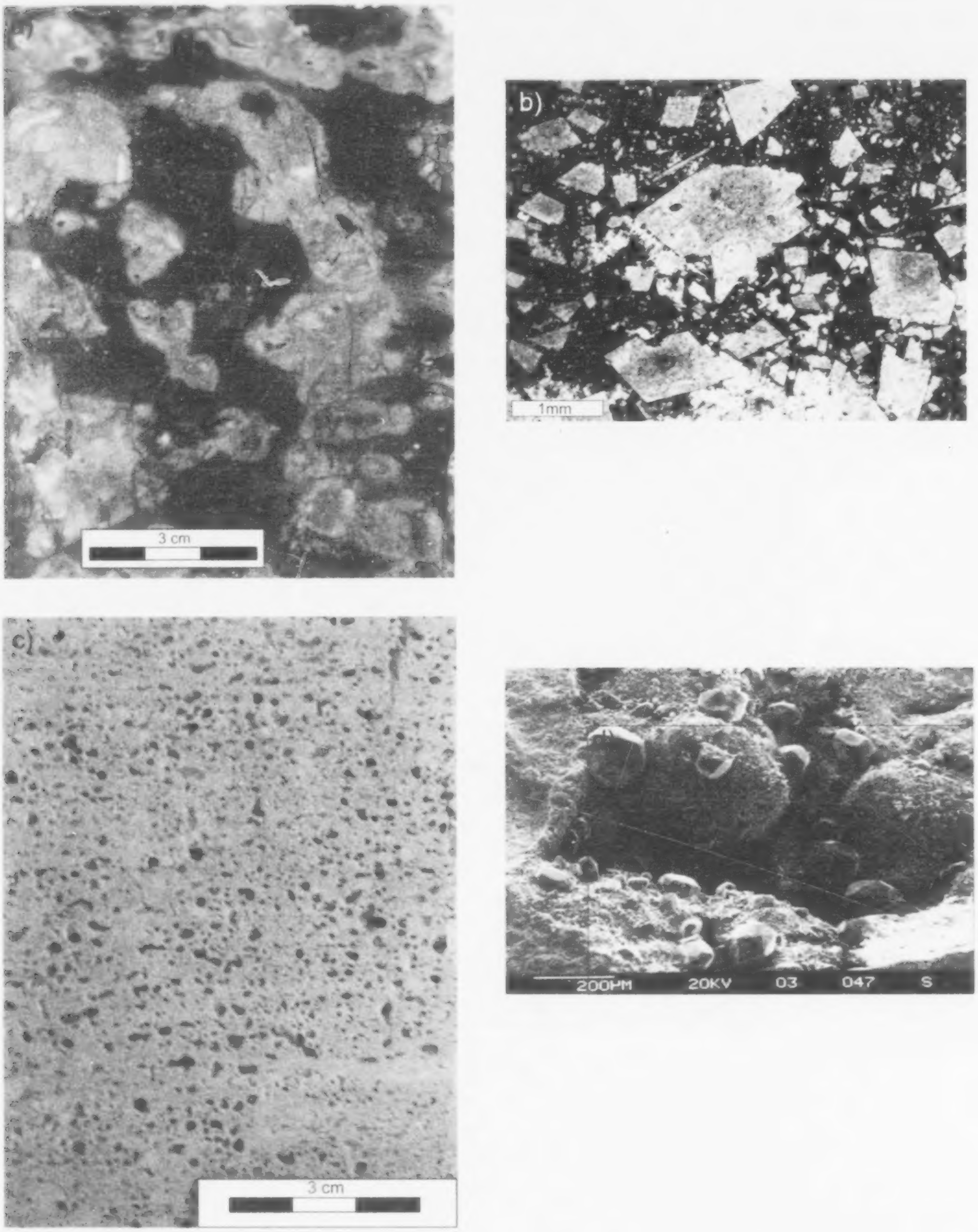


Figure 32 – Core photograph (a) and thin-section photomicrograph (b) of an Ordovician carbonate reservoir (Yeoman Formation), Minton Oil Pool, southeastern Saskatchewan. Oil is stored primarily in the partially dolomitized matrix (dark areas in [a], entire field of view in [b]). Note fossil fragments and dolomite rhombs in (b). Average porosity of this reservoir in the Minton Pool is 10.5%. Average measured permeability of the reservoir in this core (11-2-3-21W2) is 38 millidarcies. Average depth of the reservoir is 2855 m. Core photograph (c) and scanning-electron photomicrograph (d) of a Mississippian carbonate reservoir (Frobisher-Alida Beds), Alida East Oil Pool, southeastern Saskatchewan. Oil is stored primarily in the spaces between the coated carbonate grains (d) and in the fenestral pores (elongate holes in [c]). Note that oil was removed from the scanning electron micrograph sample (using a solvent bath) prior to analysis. Average porosity of reservoirs in the Alida East Pool is 16.6%. Permeability values range from <10 to >500 millidarcies; controlling factors include calcite (d) and anhydrite cementation, and fracturing. Average depth of the reservoir is 1122 m. Scale bar in (d) is 0.2 mm in length.

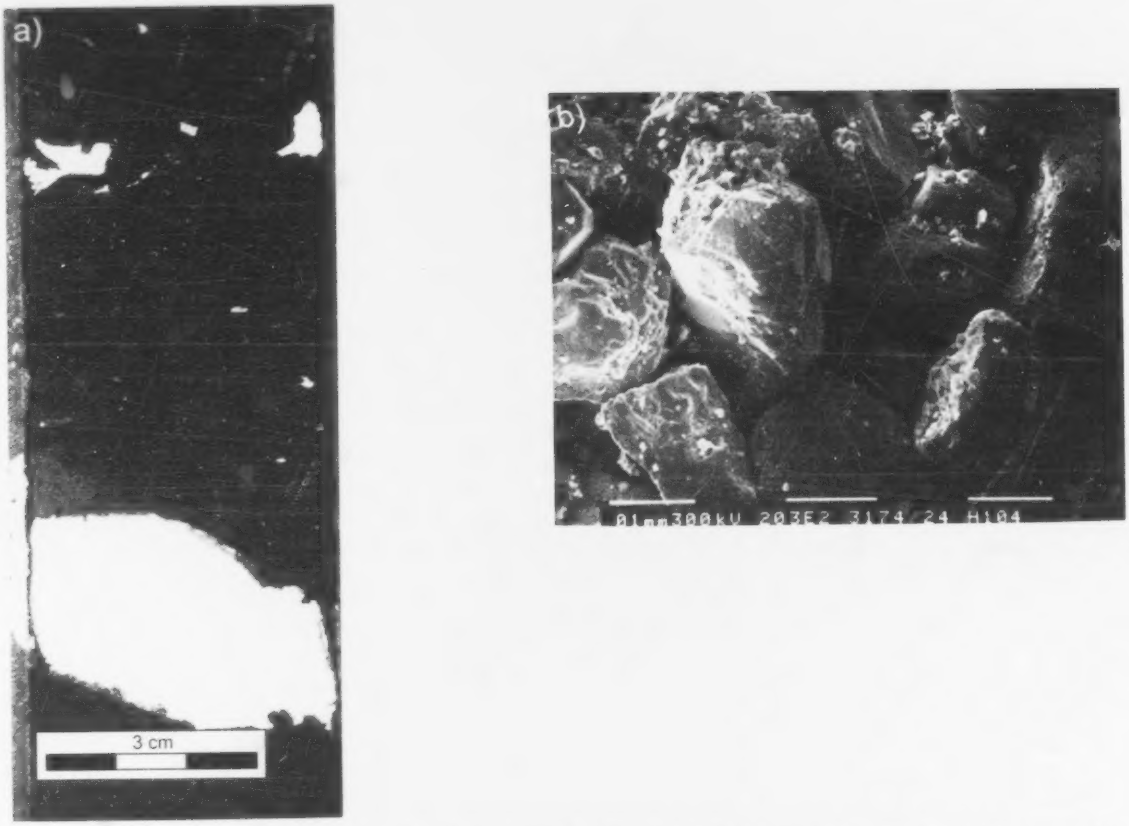


Figure 33 – Core photograph (a) and scanning-electron photomicrograph (b) of a Lower Cretaceous sandstone reservoir (General Petroleums Member, Mannville Group), Westhazel Heavy Oil Pool, west-central Saskatchewan. Oil is stored in the spaces between the sand grains. Note that oil was removed from the scanning electron micrograph sample (using a solvent bath) prior to analysis. Margins of the shale clasts (light-coloured fragments in [a]) are obscured due to penetration of oil. These sediments are interpreted as having been deposited in a channel environment. Average porosity in this reservoir in the Westhazel Pool is 35%. Permeability values are extremely high (measured average >5 darcies) due to excellent sorting of the sand grains and very limited cementation (b). Average depth of the reservoir is 485 m. Scale-bar divisions in (b) are each 0.1 mm in length.

Wapella Pool began producing medium crude; 2) the southwest (Area III), where the Fosterton Pool also began producing medium crude; and 3) the far southwest (also Area III), adjacent to the Alberta border, where the Burstall Pool began producing natural gas. The Wapella Pool produces from Red Jacket (Jurassic) and Mannville (Cretaceous) sandstones at depths of 600 to 750 m. It has yielded 4.4 x 10^6 m^3 of oil and still has recoverable reserves of 1.1 x 10^6 m^3. Despite intensive exploration, it remained the only pool of its type in the area until two discoveries in 1984. In the vicinity of the Fosterton Pool, seven other new oil pools were found in 1952. Four of these and Fosterton produced from the Roseray Sand (Jurassic), two from the Shaunavon (Jurassic), and one from the Success (Jura-Cretaceous). By the end of 1959, 31 pools had been established in this area. The Burstall Pool's initial natural-gas reservoir was the Medicine Hat Sand (Cretaceous). This was also the main initial reservoir for the much larger Hatton Gas Pool, which started production in 1953.

In 1953, light crude oil was discovered in the Kindersley area. The Whiteside and Smiley-Dewar pools began production from the Viking Sand (Cretaceous) and another four pools were operational by the end of 1959. These included Dodsland, which still has recoverable reserves of approximately 2.2 x 10^6 m^3. Also in 1953, major discoveries of oil in the Mississippian of southeastern Saskatchewan (Area IV) were made. Medium crude was produced in the Midale Pool, from the Midale and Frobisher beds at approximately 1400 m, and in the Freestone Pool, from the Frobisher-Alida beds. The Midale Pool has produced 21.1 x 10^6 m^3 of oil. By the end of 1959, 19 Mississippian medium-crude pools were in production. Light crude entered the market in 1954 from four pools, most notably the Steelman Pool, from Midale and Frobisher strata at

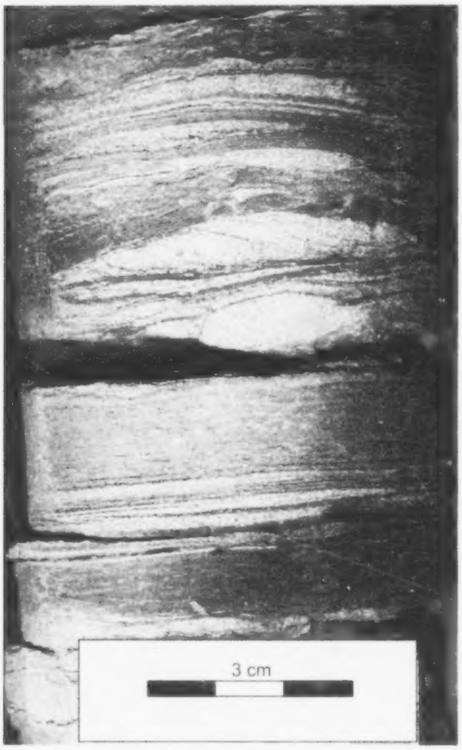


Figure 34 – Core photograph of an Upper Cretaceous natural-gas reservoir (Medicine Hat Sandstone), Hatton Pool, southwestern Saskatchewan. Average porosity in this pool is 20%. Permeability values generally range from 10 to 20 millidarcies. Average depth of the reservoir is 477 m.

about 1400 m depth. Steelman has produced some 45.4 x 10^6 m^3 of oil from both zones and has some 2.9 x 10^6 m^3 of recoverable reserves. Thirty-six pools were producing Mississippian light crude by 1960.

In the 1960s, the number of wells drilled in Saskatchewan increased to 10 069, peaking at 1 458 in 1965. As a result, 153 new pools were identified, mostly in areas already under development. Of these, 53 produced light crude and 23 produced medium crude from the Mississippian of the Estevan area; 27 produced heavy crude from the Cretaceous of the Lloydminster area; and 27 produced medium crude from the Jurassic-Cretaceous of the Swift Current area.

Of particular interest and importance was the discovery in 1963 of Ordovician oil in the Red River Formation at a depth of 3063 m in the Lake Alma district of southeastern Saskatchewan. A similar discovery was made at nearby Beaubier in 1967. Devonian oil was found at 2326 m in the Birdbear Formation in the Hummingbird area, some 16 km to the west, in 1966 and in the Kisbey area, some 113 km to the east, in 1968. Also in 1968, a good showing of Birdbear oil was noted in the Smiley area, near Kindersley. In 1968-1969, as part of a major exploration effort (the Pheasant Winnipegosis Project), 48 wells were drilled without finding oil in the target Devonian Winnipegosis Formation.

A new area of gas production was also found during the 1960s. The Beacon Hill Gas Pool, approximately 80 km north of Lloydminster in Area I, began producing gas from 274 m depth in the Mannville Group (Cretaceous) in 1963. This pool was later split to form the Beacon Hill and Beacon Hill South pools, which together had initial reserves of 5.1 x 10^9 m^3. The adjacent Pierceland Pool was discovered in 1969; it was later converted to a gas-storage reservoir.

Activity declined in the 1970s, with 6600 wells drilled and 111 new pools found. Fifty of these were in the Lloydminster heavy crude area. In the southwest, natural-gas production from Burstall, Hatton and the newly discovered Liebenthal pools increased sharply as large, shallow (335 to 460 m depth), low-permeability reserves in the Cretaceous Milk River Formation (now stratigraphically placed in the Alderson Member, Lea Park Formation) began to be exploited. Hatton's recoverable reserves in the Medicine Hat Sand and the Milk River Formation currently amount to 27.1 x 10^9 m^3. From 1978 to 1983, three companies jointly operated an exploration program, the Saskatchewan Heavy Oil Project (SHOP), in the Kindersley-Lloydminster area: 110 exploratory wells were drilled and several pools found, including Luseland (Bakken Formation of Mississippian age) in 1979. The project was also responsible for expanding the Cactus Lake Heavy Oil Pool in the basal Mannville-Bakken (Cretaceous-Mississippian).

The 1980s saw a dramatic increase in drilling activity throughout the province, with 18 068 wells drilled and 120 new pools discovered. In 1980, in Area III, a sandstone bed at the base of the Second White Speckled Shale (Cretaceous; now stratigraphically placed in the Belle Fourche Formation, Figure 15) was found to be an important natural-gas reservoir. The Bigstick Gas Pool has since produced about half of its initial established reserves of 14.7 x 10^9 m^3 from this sandstone. Deregulation of natural-gas markets in the mid-1980s led to a considerable interest in gas exploration and development. Nonassociated gas production increased by a factor of six from 1983 to 1993.

Also in the 1980s, renewed interest in deep (>2500 m) plays in southeastern Saskatchewan was initiated by the drilling of Home et al Tableland 8-22-2-9W2. In its first full month of production in September 1986, this well produced 117 m^3/day of light oil from the Devonian Winnipegosis Formation at a depth of 2580 m. Further interest was generated by the successful recompletion in 1989 of Mark et al Minton 11-2-3-

21W2 in the Winnipegosis Formation at a depth of 2610 m. This well had previously produced more than 20 x 10^3 m^3 of light crude from the Ordovician Red River Formation (Yeoman Formation; Figure 32a, b).

The 1990s saw strong exploration and development efforts continue, with 21 239 wells drilled and 115 new pools discovered. Exploration success with deep plays, combined with deep rights reversion, reduced royalties, advancements in horizontal-drilling technology and increased demand for natural gas, resulted in a decade of remarkable drilling activity in the province. Fluctuating oil prices, however, caused the yearly drilling rate to vary considerably. In 1997, provincial records were set for the number of wells drilled for oil (3608), the total number of wells drilled annually (3942) and annual oil production (23.5 x 10^6 m^3). The record for the number of gas wells drilled in a single year (1038) was reset in 1999. Discovery of the Wymark Second White Specks Gas Pool in 1998 was significant in that it extended the area of shallow-gas development to the east of Swift Current.

The discovery of significant oil reserves in Mississippian, Devonian and Ordovician rocks in the Berkley et al Midale 4-2-7-11W2 well in December 1995 was a catalyst for heightened exploration efforts for deep plays in southeastern Saskatchewan. In this well, the first year's production from the Ordovician Red River was 34.9 x 10^3 m^3, and cumulative production to the end of 2001 from all the perforated zones exceeded 105 x 10^3 m^3. Between December 1995 and December 1999, more than 280 wells were licensed to explore for Red River oil; over half of these were licensed to drill to the Precambrian basement. These exploration efforts provided valuable information about basement paleotopographic highs and their role in the formation of structural traps in overlying strata (Figure 35). This information led to discoveries of Red River oil in relatively unexplored areas in southeastern Saskatchewan, such as around Montmartre, Tyvan, Chapleau Lake and Ceylon. It also resulted in the exciting discovery, for the first time, of high-quality condensate oil in the province, found in a sandstone in the Winnipeg Formation (Ordovician) in the Tarragon Forget 11-16-07-07W2 well in 1997. This was the first time the Winnipeg Formation had proved to be an oil-producing formation in Saskatchewan and represents the deepest known production. Attempts to produce from this new target have been made in more than a dozen wells since, with varying degrees of success. The most productive well, Provident et al Hartaven 7-2-10-9W2, has yielded more than 33.3 x 10^3 m^3 condensate and 1.1692 x 10^9 m^3 gas to December 2001.

The early 2000s saw the record for number of wells drilled annually for gas broken in 2000 (1209) and again in 2001 (1395); many of these were shallow infill wells for Milk River gas. Exploration efforts in the Shackleton area of southwestern Saskatchewan in early 2002 indicate significant potential for further development of Milk River gas. New records were also set for oil production in 2000 (24.2 x 10^6 m^3) and again in 2001 (24.7 x 10^6 m^3). A significant discovery in early 2002 resulted in Saskatchewan's first-ever economic oil recovery from Silurian Interlake rocks. The Nexen Bryant 7-4T-5-7W2 well yielded 218 m^3/day from the Interlake Formation in March 2002, its third month on production. A twinned well (Nexen Bryant 7-4-5-7W2) also produced 109 m^3/d from the Red River in its first month on production.

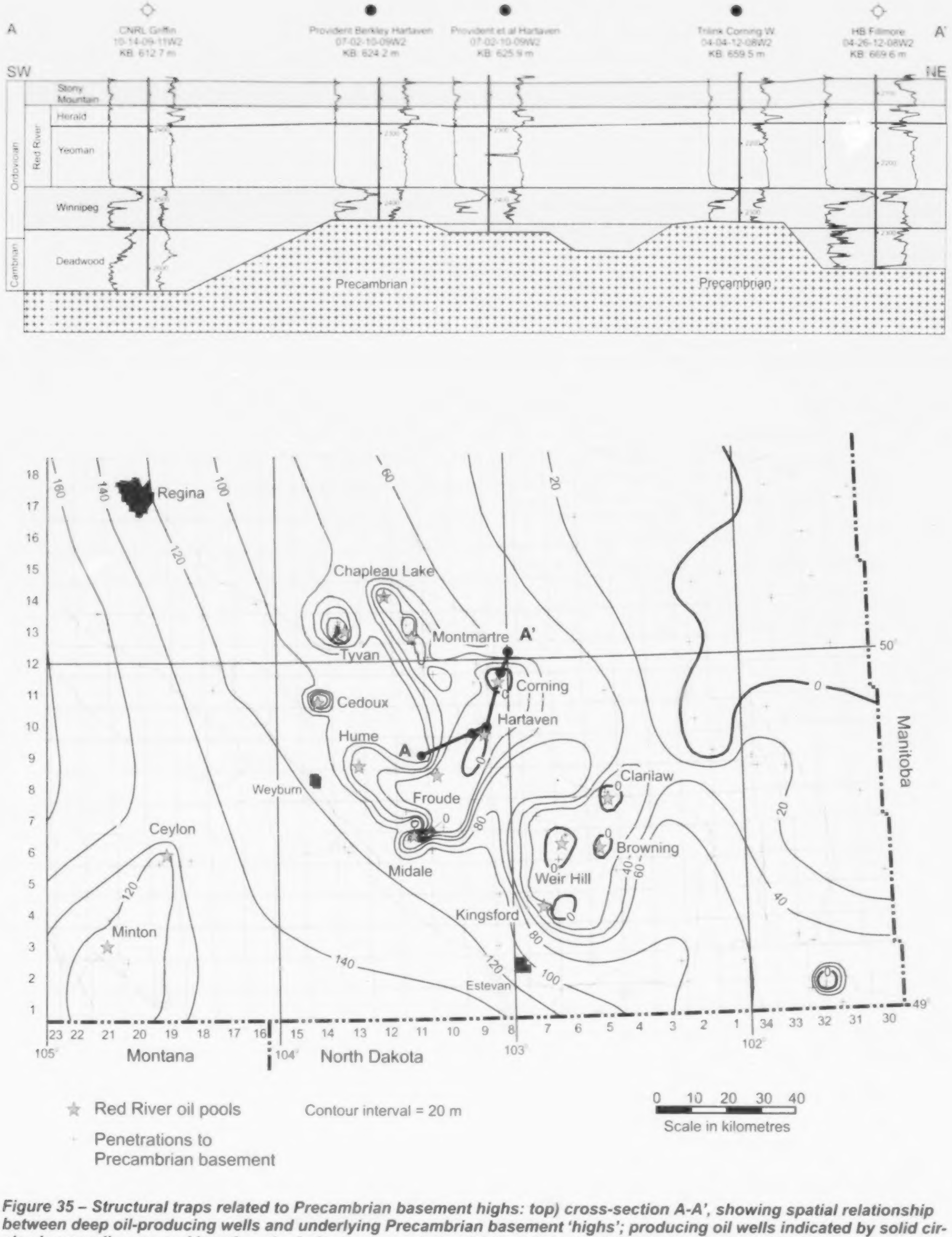
Enhanced Oil Recovery (EOR) Projects

The first operation in Saskatchewan to increase oil recovery from a producing pool was implemented in March 1956, when waterflood was applied to the Shaunavon (Jurassic) reservoir of the Dollard Pool in southwestern Saskatchewan. Later that year, waterflood projects were also initiated in the Fosterton, Gull Lake and Success oil pools, and in part of the Steelman Pool in southeastern Saskatchewan in September 1958. The process has since been approved for pools throughout the province and there are presently some 220 waterflood projects in operation.

An *in situ* combustion project, the first of its kind in Canada, was implemented in the Roseray reservoir at Battrum in November 1965. The project went through several expansions and continued as a commercial operation until 2001, when air injection was shut in. A similar project in the Fosterton Pool, started in 1970, is also shut in. Other *in situ* combustion projects were conducted in the Lloydminster area, in the Aberfeldy, Golden Lake, Eyehill, Celtic, Tangleflags and Silverdale pools, but these have all been shut in after operating as pilot projects for varying periods of time.

Steam-injection projects were initiated in the Lloydminster area in 1964, at the Dulwich, Dulwich North and Landrose pools. They were small and short lived, but were followed by similar projects at the Meota, Celtic, Aberfeldy, Tangleflags, Lone Rock and Pikes Peak pools in the late 1970s and early 1980s. Of these projects, only Pikes Peak is still operational. With the introduction of horizontal drilling in 1987, projects using steam and horizontal wells became attractive and were initiated in the Tangleflags North, Plover Lake, Cactus Lake North, Bolney, Senlac, Celtic, Edam, Tangleflags East and Kerrobert pools. Most of these are still operating.

In southeastern Saskatchewan, a hydrocarbon miscible flood was initiated in 1977 in the Willmar Pool. This pilot project was suspended prior to going into commercial operation. A miscible CO_2 pilot project was started in the Midale Unit in 1986. Upon its completion, a larger demonstration project began operation in 1992 and continued for a number of years. A commercial


A
CNRL Griffin
10-14-09-11W2
KB: 612.7 m
Provident Berkley Hartaven
07-02-10-09W2
KB: 624.2 m
Provident et al Hartaven
07-02-10-09W2
KB: 625.9 m
Trilink Corning W
04-04-12-08W2
KB: 659.5 m
HB Fillmore
04-26-12-08W2
KB: 669.6 m
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★ Red River oil pools
· Penetrations to Precambrian basement
Contour interval = 20 m
0 10 20 30 40
Scale in kilometres

Figure 35 – Structural traps related to Precambrian basement highs: top) cross-section A-A', showing spatial relationship between deep oil-producing wells and underlying Precambrian basement 'highs'; producing oil wells indicated by solid circle above well name and location, dry holes by open circle with 'arms'; bottom) Deadwood isopach (thickness) map, showing spatial relationship between Deadwood 'thins' (i.e., Precambrian 'highs') and Red River oil pools.

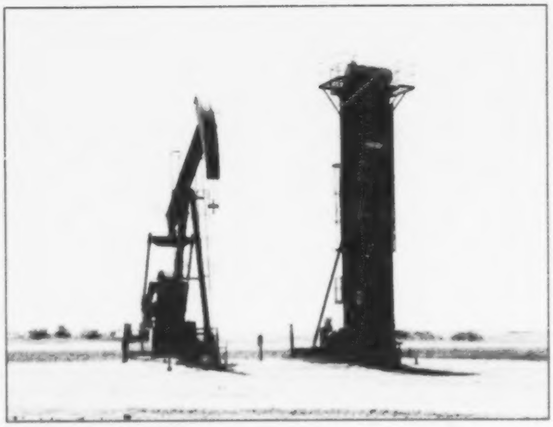

Figure 36 – Two pump jacks in the area of the miscible CO_2 flood in the Weyburn Unit. RotoFlex™ pumps, like the one on the right, allow efficient production from high-productivity, multilegged horizontal wells. Wells that produce lesser volumes of fluid have the more common beam-pump jack, like the one on the left.

CO_2 project commenced operation in the Weyburn Unit (Figure 36) in 2000. It is expected to produce at least 20.8 x 10^6 m^3 of incremental oil, through miscible or near-miscible displacement with CO_2, from a pool that has already produced 56.8 x 10^6 m^3 since 1955. The International Energy Agency (IEA) Weyburn CO_2 Monitoring and Storage Project is a multimillion dollar research program running concurrently with the Weyburn EOR project. Its aim is to evaluate the feasibility of long-term storage of CO_2 in subsurface carbonate rock.

Horizontal Wells

Horizontal drilling is an innovative technology utilized in the recovery of Saskatchewan oil. Advances in drilling technology have made possible well completions with lateral components oriented horizontally within the oil-bearing formation. To the end of 2001, more than 4500 horizontal wells had been drilled in Saskatchewan. Horizontal sections in some wells exceed 1800 m in length, while as many as six horizontal legs have been completed in others. Approximately 33% of total oil production in Saskatchewan is currently from horizontal wells.

The first horizontal well in Saskatchewan, Sceptre Murphy Tangleflags N EOR HZ 4C12-24-4C10-23-52-25W3, was drilled in the fall of 1987 as part of the Tangleflags North Steamflood Pilot, which was partially funded through the Canada-Saskatchewan Heavy Oil–Fossil Fuels Agreement. This well has a horizontal component of 406 m in a Lower Cretaceous Mannville heavy-oil reservoir. Primary production averaged 23 m^3 of oil/day. Following steam injection, the well became a prolific producer, reaching a maximum daily average of 360 m^3 of oil/day in May 1991. Additional horizontal wells and steam injectors have been added to the pilot project and total cumulative production, to February 2002, has exceeded 2.2 x 10^6 m^3 of oil.

The number of completed horizontal wells in Saskatchewan has increased dramatically since the first well in 1987 (Figure 37). The majority are in southeastern Saskatchewan, where more than 3100 have been drilled, primarily targeting Mississippian carbonate reservoirs. In the Lloydminster-Kindersley area, more than 1200 horizontal wells have been drilled in heavy-oil reservoirs and three in light-oil reservoirs. In southwestern Saskatchewan, more than 160 horizontal wells have targeted Jurassic carbonate and siliciclastic reservoirs.

The average initial production rate for horizontal wells is 25 to 30 m^3 oil/day in Lloydminster heavy-oil reservoirs and 35 to 40 m^3 oil/day in Mississippian carbonate reservoirs. Maximum production rates for more prolific horizontal wells can exceed 100 m^3 oil/day, with the Sceptre Gainsborough N HZ C5-5-A3-5-3-30W1 well achieving rates greater than 300 m^3 oil/day. The average initial production rate for conventional vertical wells in Saskatchewan is less than 10 m^3 oil/day.

Resources and Current Production

Oil production and the value of this production have risen considerably in the past decade. The production increase is largely attributed to the use of new technology, such as three-dimensional seismic surveys, horizontal drilling and positive-displacement pumps. A new oil production record of 24.7 x 10^6 m^3 was set in 2001; the value of this production was \$3.68 billion, a decline from the record \$5 billion in 2000 (Figure 29a).

Given that only 14.5% of the already discovered oil-in-place is recoverable using current technology (Table 3), there is tremendous potential for incremental produc-

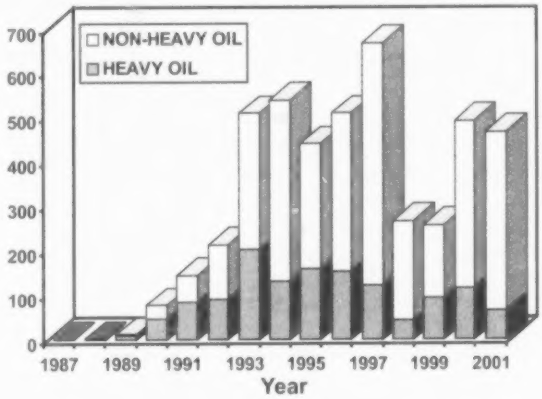

Figure 37 – Number of horizontal wells drilled per year in Saskatchewan to the end of 2001.

Table 3 – Petroleum and natural-gas reserves of Saskatchewan, 2001 (from Saskatchewan Industry and Resources, 2002).

Area	**Oil (x 10^6 m^3)**		
	Production (31-Dec-01)	**Reserves (31-Dec-01)**	**Initial oil-in-place**
Area I - Heavy	111.79	60.08	2 030.66
Area II - Heavy	41.43	27.43	650.06
Area II - Light	27.31	4.27	337.59
Area III- Medium	116.89	23.21	533.82
Area IV - Medium	127.43	38.62	782.71
Area IV - Light	172.78	31.97	1 070.70
Provincial oil total	**597.62**	**185.59**	**5 405.54**
	Gas (m^3x 10^6)		
	Production (31-Dec-01)	**Reserves (31-Dec-01)**	**Initial gas-in-place**
Provincial gas total	**137 703.60**	**75 197.90**	**280 107.60**

tion from these reservoirs using new enhanced-recovery techniques and innovative seismic, drilling and production technologies. In addition, much new oil remains to be found. Based on calculations using volumes of oil-in-place, it is estimated that only 65% of Saskatchewan's oil has been discovered to date (Lee, 1998).

Natural-gas production peaked at 8.7 x 10^9 m^3 in 1995 (Figure 29b). Recent high gas prices, however, have stimulated infill drilling in developed pools, exploration in new areas, and the re-examination and development of previously uneconomic resources. The rise in initial established reserves from 184.6 x 10^9 m^3 in 1997 to 212.7 x 10^9 m^3 in 2001 augurs well for the future of gas production in Saskatchewan, especially considering that the 2001 estimate does not include reserves in the newly developed Shackleton-Abbey area (Saskatchewan Industry and Resources, 2002). The value of natural-gas production in 2001 was $1.23 billion (Figure 29b).

Coal

History

Saskatchewan has had a long and diverse history of coal production (Figure 30). Lignite-rank coal of the Tertiary Ravenscrag Formation of southern Saskatchewan is probably one of the first of the province's mineral resources to be described and exploited by Europeans. The report on the 1857 expedition by Captain John Palliser and James Hector (the 'Palliser Expedition'; Hector, 1859) provides the first record of coal seams in southern Saskatchewan. Investigations during the expedition were conducted along the Souris River valley near Roche Percée and Estevan on the basis of native descriptions of coal-seam outcrops. In 1880, Selwyn conducted the first drilling operations in the Souris area of southeastern Saskatchewan and southwestern Manitoba, and encountered several coal seams. The works of Dowling (1914), Rose (1914, 1915, 1916) and MacLean (1917, 1918, 1921) are the earliest detailed studies of coal resources in southern Saskatchewan.

Mining of lignite probably commenced during the early 1870s in the Willow Bunch, Wood Mountain and Cypress-Shaunavon areas (Brazier, 1967). This mining was largely conducted by farmers or small groups of farmers using open-pit methods. Where overburden was excessively thick, adits were driven into the hillsides and timbered, and the lignite was mined by room-and-pillar methods (Rose, 1916). More than 400 mines, operated at various times, are recorded in the files of Saskatchewan Industry and Resources and the Geological Survey of Canada (Irvine *et al.*, 1978). A large proportion of the mines were small, satisfying the local demands of single families or small communities.

At least two small mines operated in the 1930s in Eagle Hill creek[4] valley near Kelfield, about 150 km west of Saskatoon. The Kelfield Mining and Prospecting Syndicate operation accessed the coal via decline and produced more than 1000 short tons in the winter of 1933-1934. The Barnes and Campbell operation drove a decline in 1933 and sunk a shaft in 1934. Both operations produced from a lignite-rank coal seam in the Judith River Formation that was 0.5 to 1 m in thickness (Edmunds, 1935).

The first commercial lignite production occurred near Roche Percée in 1880 when a small group of entrepreneurs shipped fuel to Winnipeg on barges down the Souris and Assiniboine rivers. Continuous commercial coal mining commenced in 1890 with the opening of the Hazzard mine in the Roche Percée area. Production from the Souris coalfields, centred roughly on Estevan, has always dominated the industry.

Lignite gained an enhanced status in the provincial economy between the early 1920s and late 1940s with its use as an industrial fuel in Regina, Moose Jaw, Brandon, Winnipeg and, to a lesser degree, Swift Current, Saskatoon and some western Ontario communities. Eastern markets were developed because of an American ban on coal exports during World War I. Later, during the depression, the incentive to use western coals was provided by subsidies granted to railroad companies (Broughton, 1988).

A fuel shortage during World War I prompted the federal and Saskatchewan governments to establish a Lignite Utilization Board to investigate methods of upgrading lignite to a more versatile fuel. Production of briquettes was the favoured option and, in 1921, a plant was established. It operated unsuccessfully until 1923, when it was closed. The plant was sold to Western Dominion Collieries Ltd. in 1927 and was modified considerably. It was subsequently resold and, in 1931, began a successful operation. Luscar Ltd. continues to operate the upgraded successor to the briquette plant, producing about 100 000 t of lignite char for barbeque briquettes each year.

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[4] unofficial place name

With the exception of small local pit operations in favourable areas, early lignite mining was largely conducted underground. The Sunlight Coal Co. was the first to attempt open-pit mining on a large scale in 1927. The experiment and the company failed due to problems with wet lignite freezing in the rail cars. In 1930, the Truax-Traer Coal Co. commenced a successful, large-scale stripping operation that heralded the gradual demise of conventional underground mining. The resulting decline in mining costs was considerable and broadened the market area to include large industrial users as far east as what is now Thunder Bay, Ontario.

By 1955, underground operations were relegated to history. Mines in the Cypress-Shaunavon and Willow Bunch areas could not compete with the more efficient mines of the Souris area, and their commercial production ended in 1954 and 1955, respectively. Lignite mining was then concentrated within a group of four large companies: Western Dominion Coal Mines Ltd. (60%), Manitoba and Saskatchewan Coal Co. (21%), Roche Percée Coal Mining Co. (10%) and Eastern Collieries (9%).

From 1940 to 1958, growth in lignite exports outpaced growth of in-province usage, which had remained fairly stable. The year 1959 marked the beginning of a rapid increase in provincial utilization, when the first unit of the Saskatchewan Power Corporation's Boundary Dam thermoelectric generating station at Estevan started up. This was followed by the second unit in 1960, and by the third, fourth and fifth units in 1969, 1973 and 1977, respectively, thereby accounting for a tripling of in-province consumption of lignite. Growth of exports during the period increased significantly through sales to Manitoba and Ontario. Figure 30 depicts lignite production in the province since the earliest years of mining. The rise in lignite production and provincial usage in the last 20 years can be attributed to the start-up of two 600 MW power units at the Coronach Power Plant in 1980 and 1982, and a 300 MW unit at the Shand generating station in 1992.

A widespread exploration program for uranium in Tertiary lignites was conducted by industry in the late 1960s. Although prospects for economic uranium deposits proved poor, the extensive shallow drilling revealed the potential for extensive coalfields in the Willow Bunch, Wood Mountain and Cypress-Shaunavon areas. In 1972, a coal evaluation program was begun under a federal-provincial agreement by the Geological Survey of Canada (GSC), Saskatchewan Mineral Resources and the Saskatchewan Research Council. The resulting report, including an atlas and an open-file microfiche catalogue of the stratigraphy in about 1200 boreholes, serves as a major reference on lignite resources in Saskatchewan (Irvine *et al.*, 1978). In the late 1980s, the GSC launched a major, GIS-based effort to improve the resource definition and to take into account cultural data, wildlife habitat, mined-out areas, physiographic features, mining parameters, coal quality, and other significant parameters affecting mineability, recoverability and economics of coal mining (Hughes *et al.*, 1989; Hughes and McDougall, 1993a, b, c). The National Coal Inventory (NCI), a web-based GIS atlas, is the final product of this research effort.

Lignite in the Tertiary Ravenscrag Formation (Figure 38)

Geology

Fine-grained, fluviolacustrine, lignite-bearing clastics (sand, silt and clay) of the Paleocene Ravenscrag Formation conformably overlie sands of the uppermost Cretaceous (Maastrichtian) Frenchman Formation. The surface of the Ravenscrag is erosional and is overlain by Tertiary and Quaternary clastics (Swift Current, Cypress Hills and Wood Mountain formations, and Empress Group). The Ravenscrag Formation extends over about 26 000 km^2 of southern Saskatchewan. It forms the northern limit of an extensive Tertiary basin centred in Montana and North Dakota, and is correlative with the Ludlow and Tongue River formations of the Fort Union Group in northwestern North Dakota. Its extent is essentially continuous from near the Manitoba

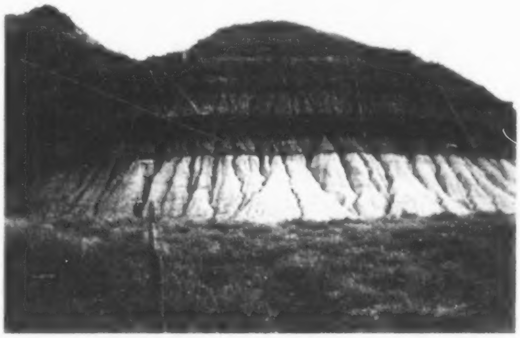

Figure 38 – Lignite bed in the Tertiary Ravenscrag Formation, which overlies the Cretaceous Whitemud Formation, Big Muddy Valley. Contact is near the base of the thickest dark lignite zone.

boundary westward to longitude 107°W (Figure 39). From here westward, the formation is present as isolated erosional remnants. The formation is thinnest in the southwestern and south-central areas of the province, where it reaches maximum thicknesses of about 76 and 200 m, respectively. In the Estevan area, the deepest part of the Tertiary basin in Saskatchewan, it attains a maximum thickness of about 305 m.

In southeastern Saskatchewan, east of longitude 104°W, the coal basin conforms to the arcuate configuration of the Cretaceous Bearpaw and Frenchman structural surfaces, indicating control by cratonic downwarping. Coal basins west of longitude 104°W, however, appear to be controlled and modified by a series of structural troughs and platforms resulting from salt-solution tectonics (Broughton, 1988).

Ravenscrag coal is of lignite rank and is widely, but discontinuously, distributed throughout the formation. Individual seams may thicken, thin, split into several thinner units or pinch out. The variable nature of the seams necessitates mapping on the basis of zones containing related seams, because zones can be recognized and traced over much greater distances than individual seams. There are four areas of significant coal accumulation in the Ravenscrag Formation: Estevan, Willow Bunch, Wood Mountain and Cypress-Shaunavon. Figure 39 illustrates these and the distribution of the major lignite depositional centres to a maximum depth of 45 m.

Irvine *et al.* (1978) treated the Willow Bunch and Wood Mountain areas as separate coalfields and adopted distinct coal-zone names for each. Hughes and McDougall (1993c), however, have established correlations between the two coalfields and produced a unified coal-zone nomenclature, in order to make the resource estimates in Table 4.

Resources and Current Production

The coal resources of southern Saskatchewan have recently been reassessed as part of the GSC's National Coal Inventory (NCI). Resource estimates are based on an analysis of geological and coal-quality data from 4631 boreholes covering the three major coalfields (Tables 4, 5). Digital models of all significant coal beds were developed utilizing specialized NCI computer software. Cultural features, such as parks and towns, that are normally excluded from mining were integrated, along with coal-quality information, into the resource-calculation process. However, cultural features were removed from resource calculations only in the Estevan Coalfield. Resources have been calculated according to standards documented by Hughes *et al.* (1989), assuming "low geological complexity" and a two-stage surface-mining recovery technique. They are categorized by strip ratio, depth, thickness, ash content, sulphur content and heating value. The two broadest resource categories, based on stripping ratios, are 1) resources of immediate interest, with ratios of up to 13:1 bank cubic metres (bcm) tonne and 2) resources of future interest, which include thinner seams with ratios of up to 20:1 bcm tonne. These are further subdivided, according to assurance of existence, into measured, indicated, inferred and speculative categories, depending on the density of well control. For details on the resource criteria, the reader is referred to Hughes and McDougall (1993a, b, c).

Present mining activity is largely concentrated near the towns of Estevan and Bienfait in southeastern Saskat-

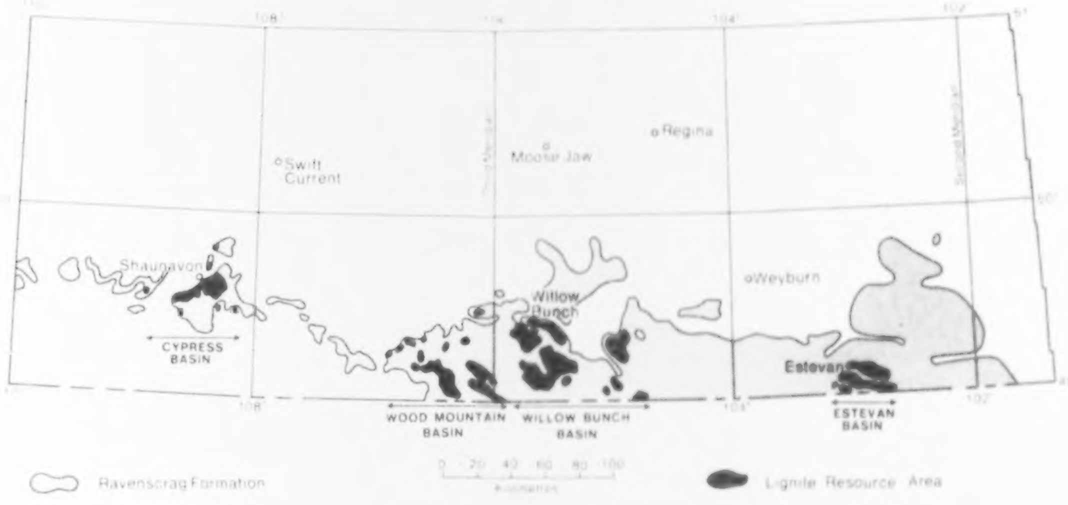

Figure 39 – Ravenscrag coalfields of southern Saskatchewan.

boundary westward to longitude 107°W (Figure 39). From here westward, the formation is present as isolated erosional remnants. The formation is thinnest in the southwestern and south-central areas of the province, where it reaches maximum thicknesses of about 76 and 200 m, respectively. In the Estevan area, the deepest part of the Tertiary basin in Saskatchewan, it attains a maximum thickness of about 305 m.

In southeastern Saskatchewan, east of longitude 104°W, the coal basin conforms to the arcuate configuration of the Cretaceous Bearpaw and Frenchman structural surfaces, indicating control by cratonic downwarping. Coal basins west of longitude 104°W, however, appear to be controlled and modified by a series of structural troughs and platforms resulting from salt-solution tectonics (Broughton, 1988).

Ravenscrag coal is of lignite rank and is widely, but discontinuously, distributed throughout the formation. Individual seams may thicken, thin, split into several thinner units or pinch out. The variable nature of the seams necessitates mapping on the basis of zones containing related seams, because zones can be recognized and traced over much greater distances than individual seams. There are four areas of significant coal accumulation in the Ravenscrag Formation: Estevan, Willow Bunch, Wood Mountain and Cypress-Shaunavon. Figure 39 illustrates these and the distribution of the major lignite depositional centres to a maximum depth of 45 m.

Irvine *et al.* (1978) treated the Willow Bunch and Wood Mountain areas as separate coalfields and adopted distinct coal-zone names for each. Hughes and McDougall (1993c), however, have established correlations between the two coalfields and produced a unified coal-zone nomenclature, in order to make the resource estimates in Table 4.

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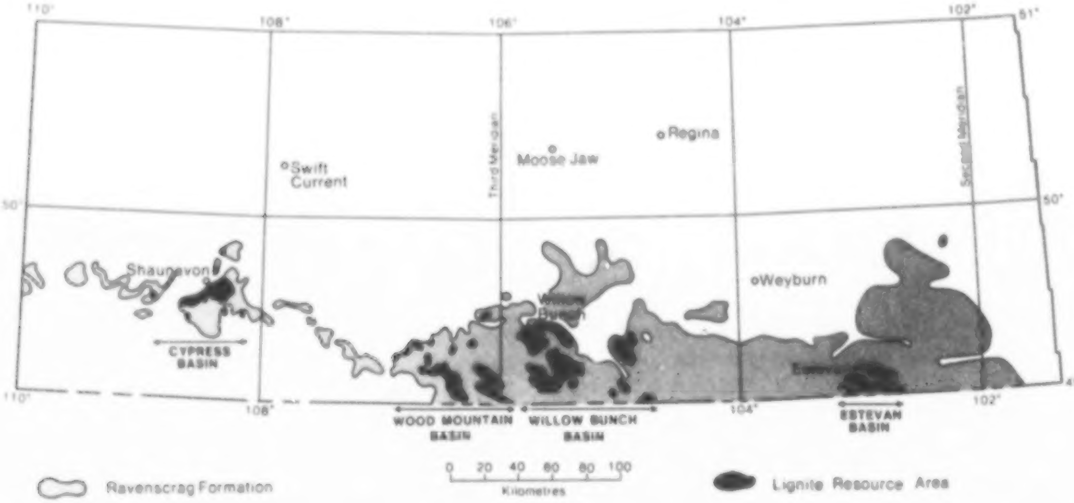


Figure 39 – Ravenscrag coalfields of southern Saskatchewan.

Table 4 – Summary of Saskatchewan lignite coal resources.

Coalfields and coal zones	Number of coal seams	Average zone thickness (m)	Mean recoverable thickness (m)	Resources of immediate interest (x 10^6 tonnes)					Resources of future interest (x 10^6 tonnes)				
				Measured	Indicated	Inferred	Speculative	Total	Measured	Indicated	Inferred	Speculative	Total
Estevan Coalfield													
Short Creek Zone	5	9.6	1.3	16.81	20.89	6.14	0.07	43.91	13.61	11.49	11.17	1.19	37.46
Roche Percée Zone	4	4.7	1.1	28.72	21.07	7.73	0.53	58.05	22.32	27.08	18.3	1.56	69.26
Souris Zone	3	1.67	1	35.58	22.46	3.98	0.45	62.47	11.74	10.12	1.72	0.69	24.27
Estevan Zone	5	4.5	2.6	177.92	190.67	63.02	1.48	433.09	33.65	39.08	58.22	2.35	133.3
Boundary Zone	7	8.46	1.1	54.17	57.26	53.3	9.06	173.79	22.72	34.23	45.46	7.88	110.29
Total				**313.2**	**312.35**	**134.17**	**11.59**	**771.31**	**104.04**	**122**	**134.87**	**13.67**	**374.58**
Willow Bunch–Wood Mountain Coalfield													
Quantock Zone	3	-	0.6	0.66	0	0.13	0	0.79	0.09	0.11	0	0	0.2
Willow Bunch Zone	5	3.98	2.6	503.53	335.11	201.08	18.38	1058.1	24.91	36.96	32.82	3.87	98.56
Poplar River Zone	3	3.42	1.3	19.01	37.78	115.51	40.73	213.03	8.5	24.37	78.52	16.03	127.42
Fremington Zone	3	2.44	1.4	30.45	46.56	59.96	20.79	157.76	13.2	37.51	96.09	16.02	162.82
Coronach Zone	3	2.82	1.6	170.85	109.85	122.5	4.81	408.01	67.22	118.89	233.29	16.01	435.41
Hart Zone	5	5.03	2	513.66	472.22	798.65	139.31	1923.84	280.41	425.22	760.7	106.39	1572.72
Fife Lake Zone	3	2.82	1.3	107.96	98.41	143.08	41.23	390.68	43.51	78.36	101.06	31.5	254.43
Landscape Zone	6	15.11	1.9	150.27	264.63	370.79	82.68	868.37	109.14	243.41	625.78	167.81	1146.14
Total				**1496.39**	**1364.56**	**1811.7**	**347.93**	**5020.58**	**546.98**	**964.83**	**1928.26**	**357.63**	**3797.7**
Shaunavon Coalfield													
Anxiety Butte Zone	4	2.96	1	21.06	22.04	22.75	1.54	67.39	9.87	21.05	35.09	4.4	70.41
Ferris D-I Sub-Zone	6	6.54	0.87	29.44	28.48	24.42	6.41	88.75	10.97	9.48	6.3	1.61	28.36
Ferris J-M Sub-Zone	4	4.3	2.2	266.68	212.91	121.28	20.51	621.38	72.21	92.82	80.91	9.86	255.8
Total				**317.18**	**263.43**	**168.45**	**28.46**	**777.52**	**93.05**	**123.35**	**122.3**	**15.87**	**354.57**
Grand total				**2126.77**	**1940.34**	**2114.32**	**387.98**	**6569.41**	**744.07**	**1210.18**	**2185.43**	**387.17**	**4526.85**

Table 5 – Summary of economic parameters for coal fields in Saskatchewan.

Coalfield parameter	Measured resources			Indicated resources			Inferred resources			Speculative resources		
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min	Max.
Estevan Coalfield												
Overall strip ratio (bcm/tonne)	8.95	0.6	13	8.62	0.42	13	7.85	0.24	13.03	7.28	0.31	12.99
Depth from surface (m)	26.35	0.3	68.05	27.02	0.3	72.69	19.9	0.3	69.54	13.21	0.3	37.09
Ash content (moist basis %)	22.25	15.63	48.82	23.1	15.8	47.73	24.94	15.84	49.32	24.25	16.48	33.49
Sulphur content (moist basis %)	0.44	0.21	0.6	0.43	0.22	0.56	0.41	0.22	0.56	0.43	0.35	0.56
Energy content (moist basis MJ/kg)	13.92	9.17	15.09	13.77	9.37	15.06	13.44	9.08	15.06	13.56	11.9	14.94
Recoverable thickness (m)	1.70	0.3	4.2	1.7	0.3	4.2	1.24	0.3	4.06	1.26	0.33	2.39
Willow Bunch-Wood Mt. Coalfield												
Overall strip ratio (bcm/tonne)	8.76	0.06	13	8.95	0.08	13.01	8.23	0.11	13.01	7.46	0.2	13
Depth from surface (m)	30.74	0.3	120.71	32.61	0.3	126.22	31.43	0.3	128.42	22.73	0.3	128.94
Ash content (moist basis %)	22.01	17.17	49.82	22.47	17.17	52.02	22.5	17.17	48.86	22.92	17.17	47.56
Sulphur content (moist basis %)	0.57	0.23	0.7	0.55	0.23	0.7	0.54	0.25	0.7	0.54	0.28	0.7
Energy content (moist basis MJ/kg)	13.94	8.97	14.83	13.85	7.11	14.83	13.85	9.16	14.83	13.78	9.37	14.83
Recoverable thickness (m)	2.04	0.3	4.2	1.83	0.3	4.2	1.6	0.3	4.2	1.35	0.3	4.16
Shaunavon Coalfield												
Overall strip ratio (bcm/tonne)	7.29	0.08	13	7.45	0.07	12.96	7.38	0.06	13.65	7.59	0.42	13
Depth from surface (m)	24.19	0.3	74.83	25.12	0.3	70.27	19.76	0.3	73.8	17.65	0.3	59.9
Ash content (moist basis %)	21.99	14.42	55.16	21.78	14.8	56.26	21.34	14.82	46.94	20.15	14.82	45.71
Sulphur content (moist basis %)	0.36	0.21	0.6	0.37	0.22	0.6	0.38	0.22	0.6	0.39	0.21	0.6
Energy content (moist basis MJ/kg)	13.98	7.5	15.31	14.01	7.51	15.24	14.09	7.38	15.24	14.3	9.71	15.24
Recoverable thickness (m)	1.8	0.3	4.19	1.71	0.3	4.03	1.3	0.3	4.15	1.1	0.3	2.22

chewan, where Luscar Ltd. operates two surface mines. The Bienfait mine, 15 km east of Estevan, produces about 2 million t of coal annually. Bienfait supplies coal for domestic markets, Ontario power plants, and the on-site char operation. Lignite char produced at Bienfait is used in the production of barbeque briquettes. Following Luscar's acquisition of Manalta in 1998, the former Boundary Dam, Shand, Utility and Costello mines were integrated into a single operation, the Boundary Dam mine. Boundary Dam supplies some 6.5 million t of coal per year to SaskPower's Boundary Dam and Shand generating stations.

The Poplar River mine (Figure 40), also acquired by Luscar Ltd. in 1998, commenced surface mining in 1980, near the town of Coronach in the Willow Bunch area. Pit operations moved in 1989 to a new location several kilometres northeast of the original mine. The mine produces about 4 million t of coal for SaskPower's Coronach generating station.

Other Coalfields

Except for the short-lived mining of coal from the Judith River Formation near Kelfield (discussed above), there has been no commercial production of coal from any stratigraphic unit other than the Ravenscrag Formation. Nevertheless, several other occurrences are noteworthy as potential local fuel sources or, in the case of more deeply buried deposits, as potential sources of coal-bed methane.

Judith River Coal at Kelfield

Edmunds (1935) discussed the geology and production of coal occurring near the village of Kelfield, about 120 km west of Saskatoon. His investigation was prompted by reports that coal was noticed by settlers in the mounds of earth excavated by gophers and in excavations for building foundations. He found Cretaceous rocks cropping out in the 80 m deep, southeast-trending, underfit valley of Eagle Hill creek, where the valley cuts through an apparent bedrock escarpment. Measured sections from the Syndicate mine indicate that the coal, approximately 0.75 m thick, is overlain by approximately 10 m of variegated shale with sand lenses (Edmunds referred to this as the pale beds of the Belly River Formation; these rocks would now be assigned to the Judith River Formation) and 3 m of glacial drift. At the Barnes mine, a thinner coal section is overlain by 3 m of sandy clay and 25 m of drift. Edmunds noted evidence of postglacial faulting in his description. The coal is considered lignite, with calorific values similar to Ravenscrag lignite (Table 6).

Saskatchewan Geological Survey archives contain numerous references, mostly of 1920s vintage, to other coal occurrences in the pale beds of the Belly River Formation: at Unity, Brock, Kerrobert, Denzil, Saskatchewan Landing, Maple Creek and others. The context or significance of these occurrences is not known.

Lower Mannville Coal South of Lac La Ronge

Flin Flon Mines Ltd. and Brascan Resources Ltd. explored for coal south of Lac La Ronge in the early

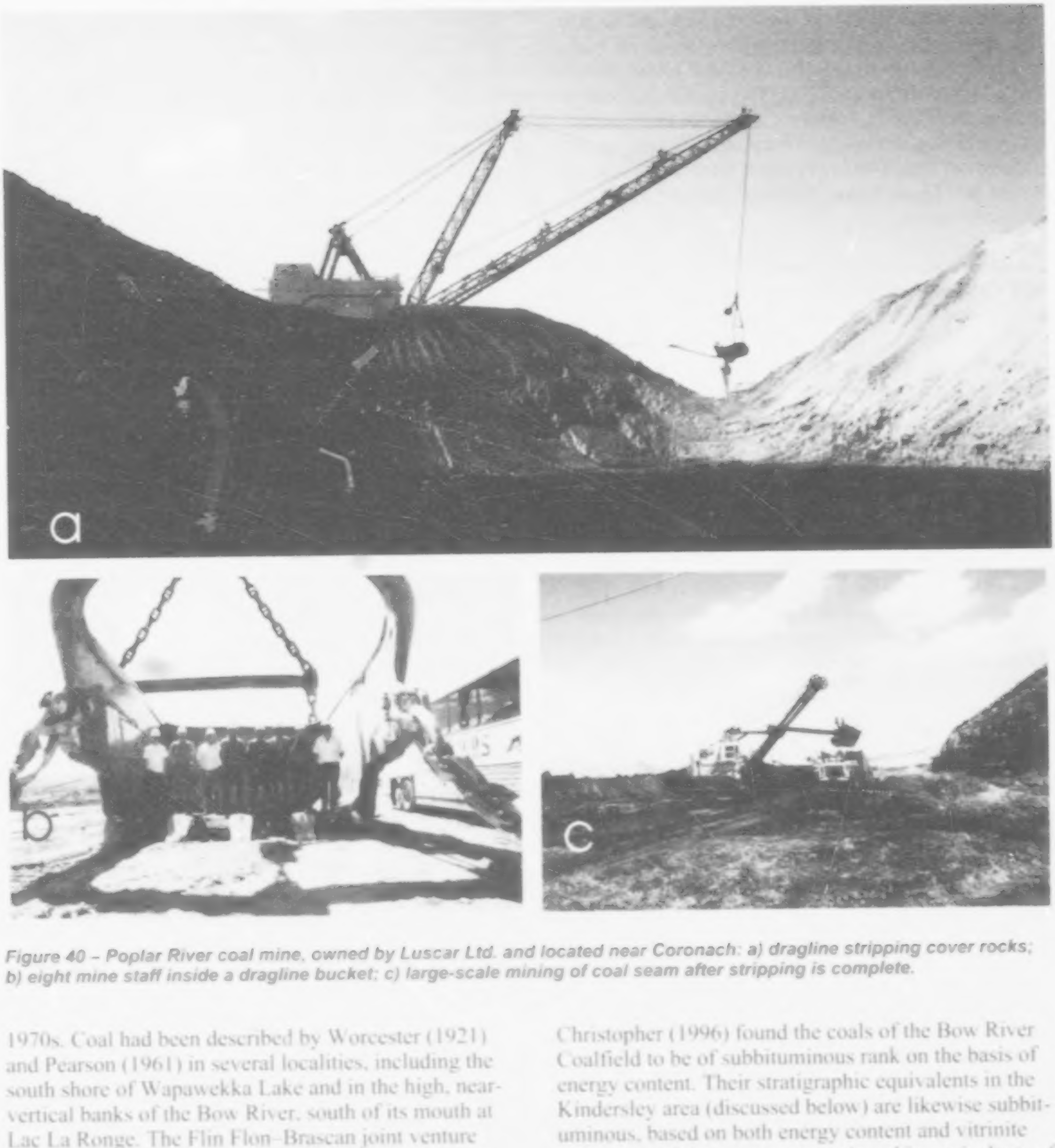


Figure 40 – Poplar River coal mine, owned by Luscar Ltd. and located near Coronach: a) dragline stripping cover rocks; b) eight mine staff inside a dragline bucket; c) large-scale mining of coal seam after stripping is complete.

1970s. Coal had been described by Worcester (1921) and Pearson (1961) in several localities, including the south shore of Wapawekka Lake and in the high, near-vertical banks of the Bow River, south of its mouth at Lac La Ronge. The Flin Flon–Brascan joint venture outlined a 50 million t resource, the Bow River Coalfield, southwest of the southwestern shore of Lac La Ronge. The coalfield is kidney-shaped in map view and roughly parallel to the shoreline; the southeastern lobe is bisected by the Bow River. One to three coal seams are present. The average net thickness of coal is 1.8 m, and it is buried beneath an average of 25 m of overburden. Stratigraphically, the coals are near the base of the Mannville Group, just above the erosional unconformity with underlying Paleozoic carbonates. In general, the coal is underlain by silty or sandy clay and is overlain by poorly consolidated quartzose sand.

Christopher (1996) found the coals of the Bow River Coalfield to be of subbituminous rank on the basis of energy content. Their stratigraphic equivalents in the Kindersley area (discussed below) are likewise subbituminous, based on both energy content and vitrinite reflectance. Other apparent stratigraphic equivalents of the Bow River Coalfield have been recorded to the south, in petroleum-exploration wells at Montreal Lake and from diamond-drill holes in the Choiceland iron deposit.

Lower Mannville Coal, West-Central Saskatchewan

Coal seams are noted in many petroleum-well logs in west-central Saskatchewan, where their continuity is such that they are used as stratigraphic markers. In the mid-1980s, Luscar Ltd. investigated the economic potential of this coal region by examining and correlating more than 400 electric logs, and sampling coal from at least three petroleum-well cores. They found the coal to be of subbituminous rank (Table 6) and, in the general area of Kerrobert, about 130 km west of Saskatoon, delineated more than 1.7 billion t of coal in four subsurface coalfields, defined by a minimum net coal thickness of 2 m. The field judged most promising was termed the 'Plover Lake Coalfield', defined in 49 petroleum wells.

Luscar completed a well (Luscar Cosine 5-5-35-28W3) for the purpose of coring the coal and the overlying and underlying sedimentary rocks. They recovered 4 m of coal, including a 0.4 m mudstone parting, from the 61 m core and confirmed the subbituminous rank of the coal (Table 6).

Stratigraphically, the coal is in the lower Mannville Group and is informally designated the Sparky Coal. The top of the Sparky Coal is at an average depth of 830 m below surface in the Plover Lake Coalfield. The coal is separated from the underlying Sparky Sand by 2 to 8 m of siltstones and mudstones and from the overlying Waseca Sand by 5 to 18 m of similar rock. The mechanical competency of the rocks below the coal seam and the high hydrostatic pressures in the sands led Luscar to conclude that underground mining of the Sparky Coal would not be feasible, and the project was abandoned.

Lower Mannville coals have been documented in other areas of west-central Saskatchewan, including northeast of Kerrobert (Gulf SHOP et al Druid 16-13-34-22W3), south of Smiley (Bison Whiteside 13-30-30-25W3) and northeast of Sceptre (CDR Lemsford 12-30-22-22W3). The Sparky and Waseca sands are widespread, sheet-like bodies that have been prolific natural-gas producers for many years. With the increasing awareness of the potential of coal-bed methane as a source of natural gas, there has been some speculation that the ultimate source of the Sparky and Waseca gas could be, at least in part, the widespread coal that lies between the two sands. This possibility has not been investigated.

Mineral Resources

The search for metallic minerals in Saskatchewan began in about 1859, following the discovery of gold in the North Saskatchewan River. Dr. James Hector of the Palliser expedition (Hector, 1859), in the vicinity of Edmonton in that year, observed a few specimens of gold being worked out of river sediments. Apparently the gold was discovered by prospectors making their way to the Cariboo gold rush in the interior of British Columbia. Much of the activity on the river was occurring around Edmonton, but flour gold was found as far downstream as Prince Albert. Small-scale placer mining has been taking place ever since.

Mineral exploration on the Precambrian Shield followed mapping by the Geological Survey of Canada. During 1892-1893, J.B. Tyrrell and his assistant, D.B. Dowling, surveyed many of the major waterways in northern Saskatchewan (Tyrrell and Dowling, 1896). Of particular interest to later explorers was the recognition of noritic rocks on the north shore of Pine Channel at the east end of Lake Athabasca. In 1896, Tyrrell (1902) returned to Saskatchewan and made a further survey in the Flin Flon area, noting the presence of quartz veins on Amisk Lake. These would later prove to be significant. W. McInnes (1909, 1910, 1913) worked in the province from 1908 to 1910, investigating the geology of the Shield edge between Lac La Ronge and the Manitoba border. He reported copper sulphides at Moose Point on the northwest shore of Lac La Ronge, at a location that would become, in 1966, the site of the Anglo-Rouyn copper mine.

During the years following World War II, the continuing search for metals was aided by an ongoing mapping program conducted by the newly formed Saskatchewan Geological Survey, founded in 1948 as part of the Mineral Resources Branch of the Department of Natural Resources. Over the years that followed, the provincial government became further involved in mineral exploration through the provision of incentives and direct assistance to prospectors. The introduction of newly developed airborne-geophysical surveys by both industry and government opened up in northern Saskatchewan, as elsewhere, a much larger area to exploration.

In the last decade, exploration expenditures in the province have remained strong, consistently above $20 million, and approached $40 million for several years in the mid-1990s (Figure 41). Uranium has been the most important commodity, and the announcement in 2002 by Cameco Resources Ltd. of the Millennium zone discovery on the Cree Extension Project points to continued, robust exploration in the Athabasca Basin in the future. Diamonds have also emerged as a strong exploration focus in the last decade, following the discovery of diamond-bearing kimberlite in Phanerozoic strata northeast of Prince Albert in 1989.

Currently, the only metallic minerals produced in Saskatchewan are uranium, gold, copper, zinc, silver and cadmium. Nevertheless, there are significant historical copper and copper-zinc mines, and numerous, smaller past-producers of lead, nickel, selenium, tellurium, platinum and palladium. Modern mining began in 1930 in the historic, Flin Flon Proterozoic volcanogenic massive-sulphide (VMS) mining camp, located on the Saskatchewan-Manitoba boundary. Gold production began in 1939 at the Box mine in the Beaverlodge camp, some 14 years before the first uranium mine, the Ace-Fay-Verna, opened in 1953; uranium was produced from 16 operating mines before the Beaverlodge camp shut down some 30 years later. The total value of metallic-

Table 6 – Characteristics of Cretaceous coals in Saskatchewan.

Name and location[1]	SIR assessment file no.	Formation	N[2]	Sample no.	Depth (m)	Weighted average of N samples							
						Proximate analysis[3] (100%)							
						Moisture (%)	Ash (%)	Volatile matter (%)	Fixed carbon (%)	Sulphur (%, AR)	Calorific value (btu/lb., AR)	Mean vitrinite reflectance (Ro)	Coal rank
Mesa HNM Hossier, 16-3-32-27W3	72-N-0001	Sparky coal seam (Mannville)	1	C	826.5-829.3	9.31	7.28	37.92	45.49	3.24	10,365	0.37	Sub-bituminous A
Major No 1, 5-22-33-25W3	72-N-0001	Blairmore Fm., Sparky coal seam	1	-	779.6-782.0	8.89	16.50	33.19	41.42	0.70	8,540	0.38	Sub-bituminous A/B
Pacific Smiley, 13-30-30-25W3	72-N-0001	Blairmore Fm., Sparky coal seam	10	A to J	Unknown	8.04	16.50	34.75	40.71	4.27	9,203	0.37	Sub-bituminous B
Pacific Smiley, 13-30-30-25W3	72-N-0001	Sparky coal seam	5	2992-74 to 2996-74	873.3-880.8	8.90	21.68	31.92	37.50	4.79	8,434	-	-
Luscar Cosine, 5-5-35-28W3 A	72-N-0001	Sparky coal seam	6	1-6	789.2-791.62	15.46	24.50	25.98	34.06	2.12	7,608.65	0.39	Sub-bituminous A
Luscar Cosine, 5-5-35-28W3 B	72-N-0001	Sparky coal seam	3	7-9	792.07-793.11	11.82	40.41	22.69	25.08	2.31	5,852.52	-	-
Husky N Hossier, 14-14-32-27W3	72-N-0001	Sparky coal seam (Mannville)	4	1, 2B, 3, 4	Top: 853	6.75	26.26	30.31	36.68	3.18	8,364.25	-	-
CDR NE Lemsford, 12-30-22-22W3	72-N-0001	-	1	1C	Unknown	6.97	35.08	32.25	25.70	7.02	6,710	-	-
CDR NE Lemsford, 12-30-22-22W3	72-N-0001	-	1	2	Unknown	8.34	26.82	28.83	36.01	11.93	5,700	0.47	-
C1GOL, 4-10-34-24W3	72-N-0001	-	2	1D, 2D	827.2-835.1	7.3	15.38	33.63	43.69	4.15	9,275	-	-
PEX Shop Cactus, Lake 7-25-35-28W3	72-N-0001	-	1	-	868-869.5	7.18	62.17	16.73	13.92	1.75	2,746	-	-
Gulf Shop, 16-13-34-22W3	72-N-0001	-	1	2C	Unknown	5.44	46.97	24.49	23.10	4.21	4,166	-	-
Gulf Shop, 16-13-34-22W3	72-N-0001	-	1	1B	Unknown	6.95	15.66	35.41	41.98	6.28	9,443	0.40	-
Bow River Coal Field, T68 R22W2	73-I-14-0015	Bow River Coal Field	-	-	20-25	30	20	23	27.00	2	6,000-6,500	-	Lignite A
Kelfield area (Barnes mine), 2-12-34-20W3	C-114, Table 2	Pale and variegated beds, Oldman Fm.	-	-	27.43	15.17	-	-	-	-	8,023 (air dried, not ash free?)	-	Lignite
Kelfield area (Syndicate mine), 12-7-34-19W3	C-114, Table 2	Pale and variegated beds, Oldman Fm.	-	-	12.19-12.34	27.06	-	-	-	-	8,949 (air dried, not ash free?)	-	-
Charlton 14-20-16W3, between Cabri & Sask Landing	C-122	Belly River Fm.	-	-	Outcrop	17.4 (air dried)	4.1	35.2	43.2	-	-	-	-
Dowling 14-20-16W3, Sask Landing area	C-122	Belly River Fm.	-	-	Outcrop	16.05 (air dried)	6.55	55.05	22.35	-	-	-	-
Kerrobert	C-122	Belly River Fm.	-	-	Outcrop	21.32 (air dried)	4.75	34	39.93	-	-	-	-
Unity	C-122	Belly River Fm.	-	-	Outcrop	16.29 (air dried)	12.88	32.19	38.64	-	-	-	-
Brock, 22-28-20W3	C-122	Belly River Fm., Galt coal seam	-	-	39.62	19.35 (air dried)	22.35	26.92	31.38	-	-	-	-

Note: Values have been changed from incorrect data in Assessment File 72-N-0001

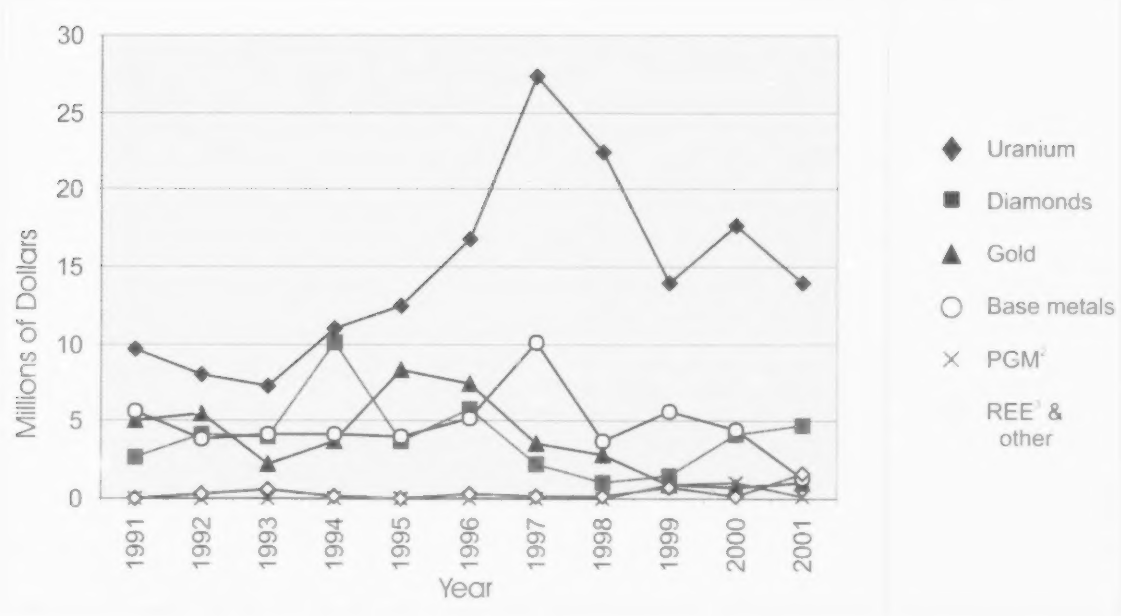
[1] complete LSD signifies oil-well sample; all other samples are from outcrop

[2] number of samples analyzed

[3] samples 'as received' (AR)

mineral sales has fluctuated considerably since 1932 (Figure 42). Uranium has dominated sales since 1975, when production began at Rabbit Lake, the first of the unconformity-type, Athabasca Basin uranium deposits. The fall in base-metal sales that began in the mid-1980s reflects the depletion of ore in the Flin Flon ore body, where mining began in 1930. The rise in precious-metal sales that began in 1985 is the result of the start-up of gold mines north of La Ronge.

Industrial minerals and rocks in Saskatchewan have been sought after and used in the daily lives and commerce of man since the time of earliest known human habitation, at least 12 000 years ago. Usage of natural mineral materials is recorded by the presence of stone points of the Clovis type in many archeological sites throughout Saskatchewan. Remnants of pottery dating back more than 2000 years are found mainly south of the Churchill River. Written records of mineral occurrences commence shortly after the arrival of the earliest European explorers, traders and settlers, such as Henry



	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002[1]
Uranium	9.69	8.07	7.25	11.06	12.54	16.76	27.32	22.4	14.00	17.74	14.02	15.87
Diamonds	2.67	4.19	3.99	10.14	3.76	5.72	2.30	1.01	1.43	4.11	4.77	7.29
Gold	5.03	5.5	2.17	3.67	8.38	7.42	3.5	2.76	0.95	0.73	1.01	2.61
Base Metals	5.65	3.8	4.15	4.18	3.96	5.2	10.11	3.68	5.64	4.47	1.39	1.83
PGM[2]	---	---	---	---	---	---	---	---	0.91	1.02	0.14	0.80
REE & Other[3]	0	0.25	0.55	0.1	---	0.32	0.15	0.21	0.81	0.14	1.58	1.72
Total	23.04	21.81	18.11	29.15	28.64	35.42	43.38	30.06	23.74	28.21	22.91	30.12

Data published annually in Exploration and Development Highlights, Saskatchewan Industry and Resources.

[1] Estimated from the annual mineral-industry survey done by the Saskatchewan Resident Geologists.

[2] Platinum-group metals.

[3] Rare-earth elements.

Figure 41 – Exploration expenditures in Saskatchewan, by commodity, 1991-2002.

Kelsey, La Verendrye, Samuel Hearne, Alexander Mackenzie and the fur traders of Fort Carlton and Cumberland House in the late 18th and early 19th centuries. Sir John Richardson was the first to explore the mineral potential of the province when he arrived in Rupert's Land in 1820 and examined Silurian dolomites at Cumberland House (Kupsch, 1955). The territorial rights to Rupert's Land were held by the Hudson's Bay Company until 1870, when they were acquired by the Dominion of Canada. The acquisition laid the foundation for geological investigations in the region by the Geological Survey of Canada, which was established in 1842. Among the earliest of these geological surveys in the sedimentary basin of the province were those conducted by Hector (1859), Hind (1859), Dawson (1875), Selwyn (1880) and McConnell (1885).

When Saskatchewan attained province status in 1905, the Government of Canada retained the rights to its natural resources and the responsibility for conducting geological surveys. Much of the geological work on industrial minerals was conducted by the Canada Mines Branch, formed in 1915. By 1920, the province took a more active role in resource development and established the Saskatchewan Bureau of Labour and Industries. The Bureau initially farmed out much of the exploratory and evaluation work to W.G. Worcester, a ceramic engineer at the University of Saskatchewan. In 1929, the university's newly formed Department of Geology took on an expanding role in the work. Sedimentary geological investigations were, at that time, conducted by Professor F.H. Edmunds.

Industrial minerals have played a significant role in the mining economy of Saskatchewan during the past two decades (Figure 43). Although industrial minerals production has grown steadily, and in some cases spectacularly, between about 1972 and 1982, the bulk of the growth is attributed to the potash industry.

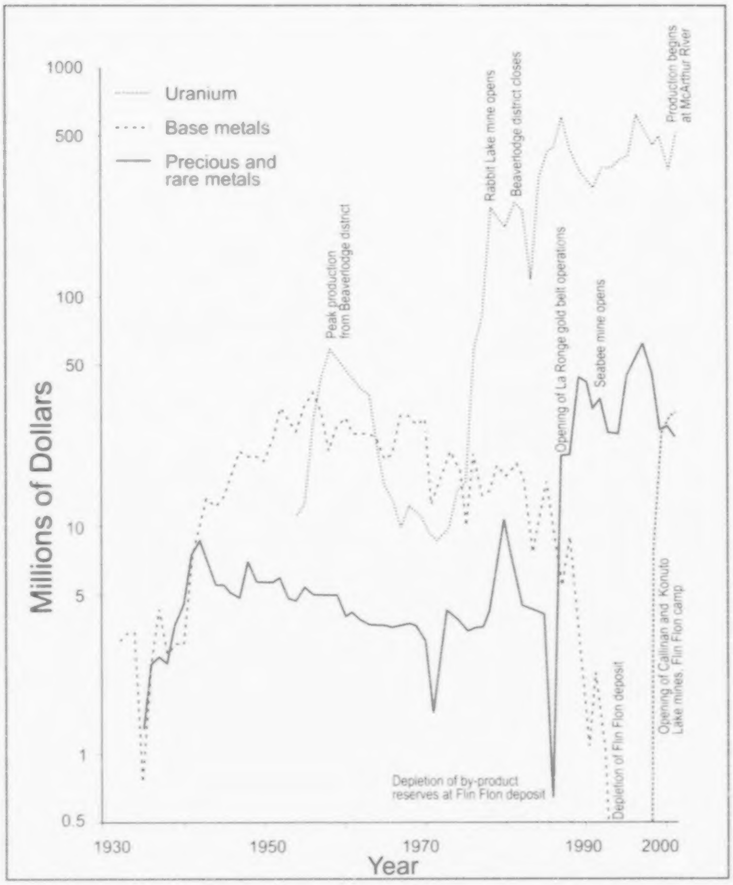


Figure 42 – Total value of metallic-mineral sales in Saskatchewan, 1930-2001. Note the logarithmic scale on the y-axis (dollar value), used to accommodate large disparities in the value of uranium compared to other metals.

Potash

Potash is the most important mineral resource for the Saskatchewan economy; in 2001, it accounted for $1.6 billion, or about 9%, of the total value of exports from the province (Figure 44). Potash is primarily used in the manufacture of fertilizer, although newly developed potash-based water-softening salt is an emerging high-value product. As a result of a series of expansions in the 1970s and 1980s, the Saskatchewan potash industry now ranks as the world's largest producer and exporter of potash (Pearse, 2000), accounting for 33% of world production and capacity, and about 43% of world trade.

History

Intensified petroleum exploration during World War II led to the discovery of potash in south-central Saskatchewan in 1942, near the town of Radville, at a depth of 2332 m. This was followed in 1943 by a similar discovery near Ogema, and in 1946 a cored well returned 21.6% K_2O over 3.35 m at a depth of 1056 m (Fuzesy, 1982). Ten years elapsed before a well was drilled specifically for potash evaluation.

The first attempt at commercial potash mining in Saskatchewan was that of Western Potash Corporation Ltd. in 1951. After failing at solution mining near Unity, the company began sinking a mining shaft in 1952. Difficulties with water inflow followed, and the shaft was abandoned and sealed in 1968.

The Potash Company of America initiated potash mining at Patience Lake, near Saskatoon, in 1958. With the exception of an interruption between 1959 and 1965 due to brine inflow, the mine was essentially in continuous production until 1987, when brine inflow from older workings caused production to be suspended. Between 1962 and 1970, about 40 companies were involved in potash exploration. Nine successful ventures, in addition to the Patience Lake mine, resulted from these efforts.

Geology

Saskatchewan's potash deposits are part of a vast potash-bearing region extending across southern Saskatchewan and into Manitoba, Montana and North Dakota (Figure 45). The potash occurs near the top of a thick sequence of halite and anhydrite that makes up the Middle Devonian Prairie Evaporite Formation of the Elk Point Group (Figure 46). In Saskatchewan, this formation is at a depth of 400 to 2740 m and attains a maximum thickness of about 213 m. The upper 60 m of the formation contain four distinct potash-bearing members (Figure 46). These are, in ascending order, the Esterhazy (EM), White Bear (WBM), Belle Plaine (BPM) and Patience Lake (PLM) members. The members, commonly 6 to 15 m thick, are separated by 1 to 45 m sections of halite and composed of one or more individual potash beds up to 7 m thick (Guliov, 1993). The ore, called 'sylvinite', consists of a mixture of halite

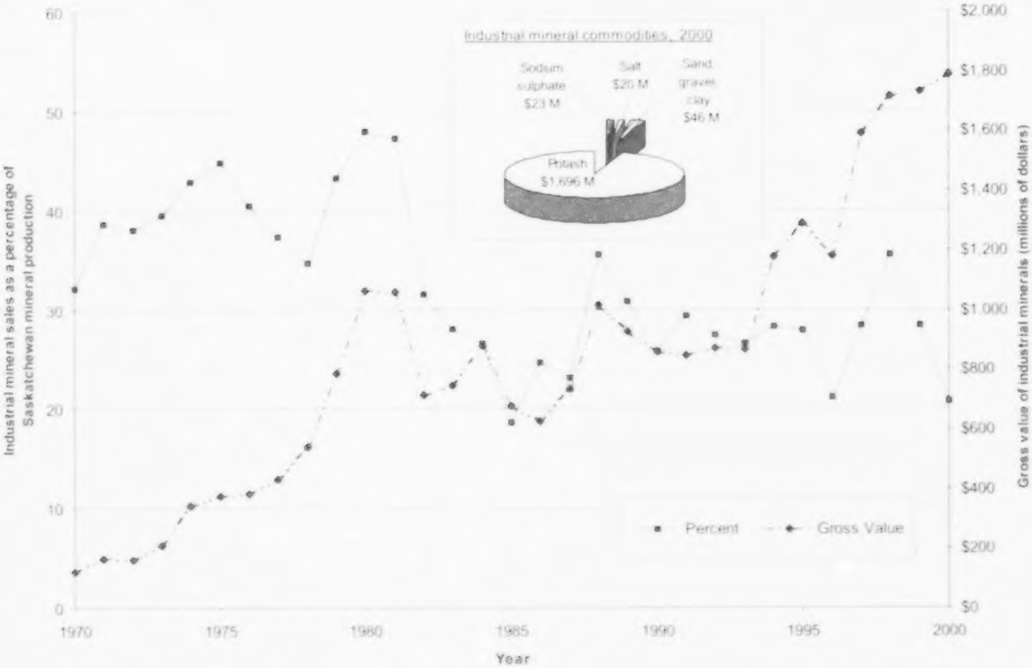


Figure 43 – Contribution of industrial minerals to the value of mineral sales in Saskatchewan, 1970-1992.

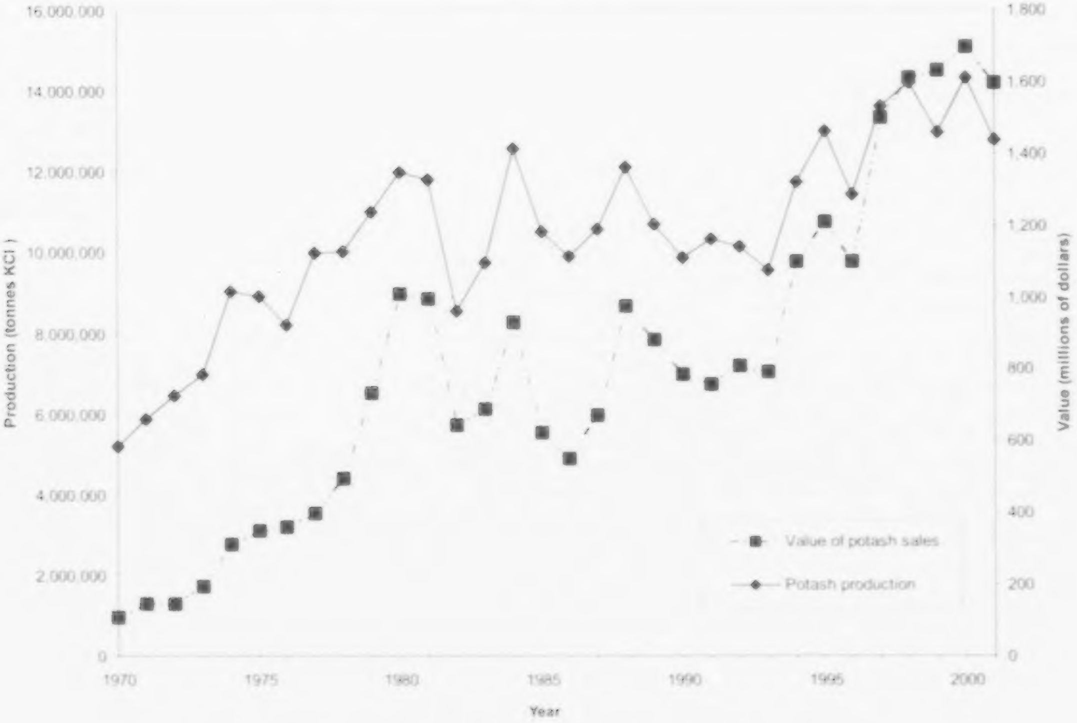


Figure 44 – Saskatchewan potash production and sales value, 1970-2001.

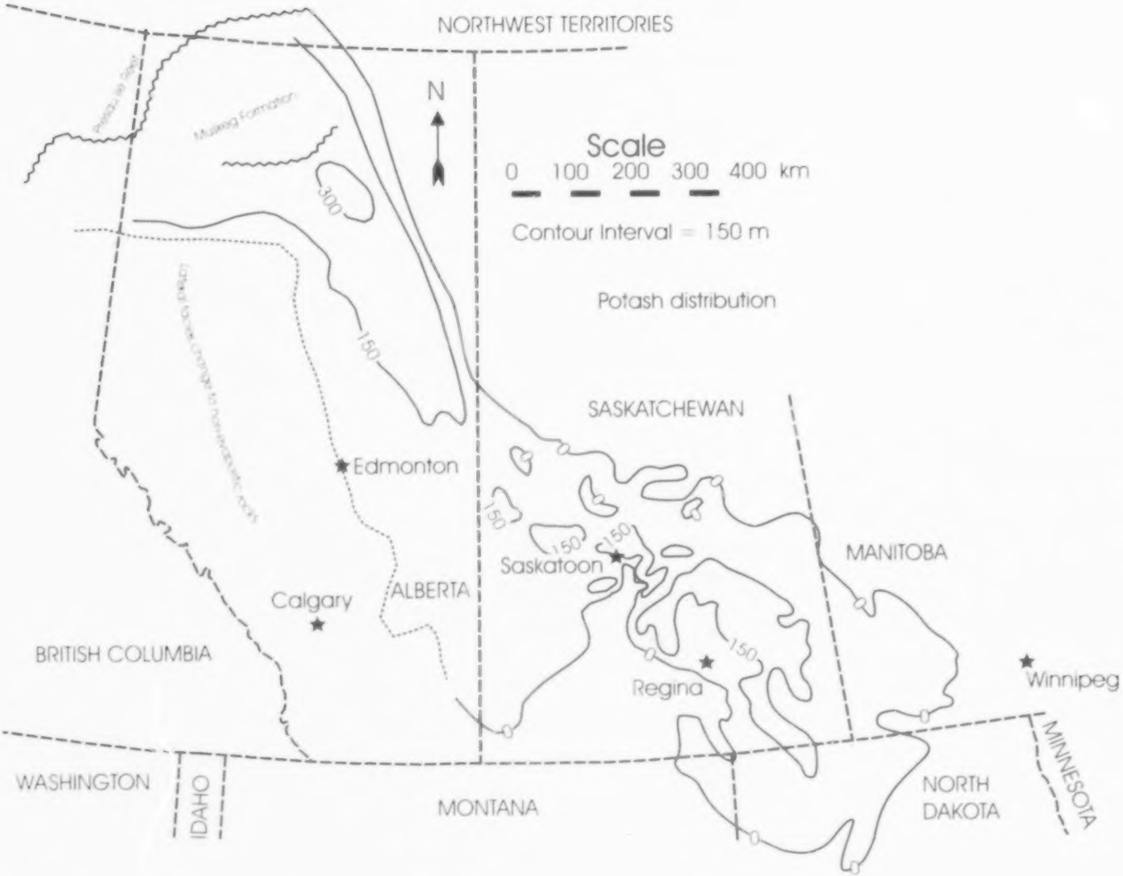

NORTHWEST TERRITORIES
Muskeg Formation
Lateral facies change to nonevaporitic rocks
N
Scale
0 100 200 300 400 km
Contour Interval = 150 m
Potash distribution
300
150
150
150
150
150
SASKATCHEWAN
Edmonton
Saskatoon
MANITOBA
Calgary
ALBERTA
BRITISH COLUMBIA
Regina
Winnipeg
WASHINGTON
IDAHO
MONTANA
NORTH DAKOTA
MINNESOTA

Figure 45 – Prairie Evaporite isopachs and general distribution of potash.

(NaCl), sylvite (KCl), carnallite ($KCl \cdot MgCl_2 \cdot 6H_2O$) and variable amounts of insoluble minerals. It averages between 21 and 27% K_2O, and locally exceeds 30% (Fuzesy, 1982).

Resources and Current Production

The potash industry in Saskatchewan comprises two solution mines and eight conventional mines, which together account for about 95% of Canadian potash production, up from about 88% in the early 1990s. Conventional underground mining is conducted to depths of about 1100 m, whereas deeper ore is more suited to solution mining methods (Figures 47, 48). In recent years, annual sales of Saskatchewan potash have totalled more than $1.5 billion per year. Ownership and production capacity of the 10 producing potash mines is summarized in Table 7. The production capacity of the industry has risen considerably through expansion during the 1980s, and hit a high of more than 14 million t of potassium chloride (KCl) in 2000, valued at more than $1.6 billion (Figure 44). Reserve estimates are upwards of 14.0 billion t by conventional mining (Barry, 1981) and more than 42 billion t by solution mining (Guliov, 1993).

Technical breakthroughs have been critical to the success of large-scale underground mining of potash in Saskatchewan. The Potash Corporation of Saskatchewan (PCS) mine at Patience Lake was closed due to flooding in 1987. A solution-mining pilot test was conducted successfully by May 1988, and the company returned to production as a solution mine in 1989, at a cost of $20 million. Natural precipitation of the potash at this mine takes place during October to April in surface ponds with a total area of about 50 ha. IMC Kalium's Esterhazy K-2 mine started having water-inflow problems in 1985 and suffered steadily increasing flow rates in the early 1990s. In 1997, a new grouting and supporting system test began, with hopes of reducing the rate of inflow by more than half. This required a structural consolidation program, using a sand-concrete backfill system, to support the underground area. By 2000, the water-inflow problem had no significant effect on production (Pearse, 2000). At the PCS

Cory mine, $CaCl_2$-rich (28%) brine inflow has been utilized to produce calcium chloride. In 1998, IMC Global announced expansion plans for its Belle Plaine facility, slated for completion in 2004.

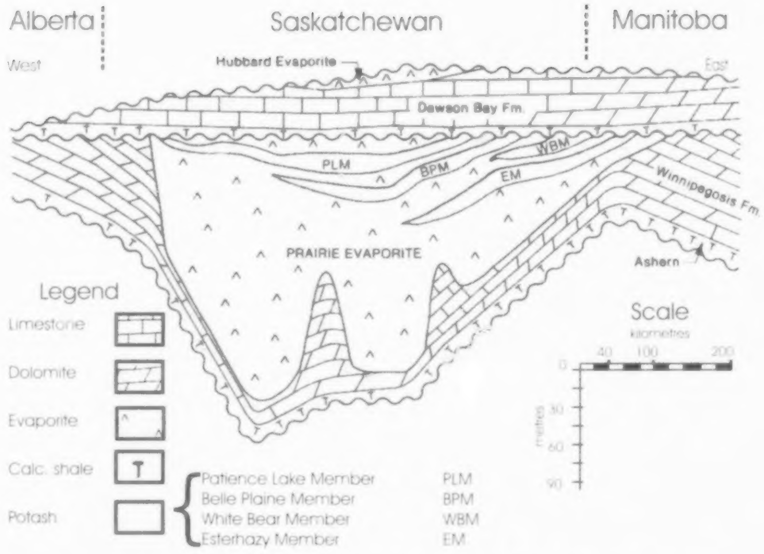


Figure 46 – Schematic cross-section through the Prairie Evaporite, looking north.

Uranium

Uranium is currently the second most important mineral resource for the Saskatchewan economy, accounting for some $562M, or 3%, of the total value of provincial exports. Further, it has dominated the mineral-exploration sector in Saskatchewan since the Government of Canada lifted the ban on uranium exploration in 1947.

Uranium in the province occurs in two main areas, representing two different geological environments and two different metallogenic origins: epigenetic veins of the Beaverlodge district along the north shore of Lake Athabasca, and unconformity-type deposits located mostly near the eastern margin of the Athabasca Basin. Production occurred from the former between 1953 and 1982, and started from the latter in 1976 (Figure 49). Exploration and development in the Beaverlodge camp peaked in 1959, and quickly declined thereafter following the cancellation of sales contracts with the United States that same year. Discovery in 1968 of a new, unconformity-related, high-grade type of deposit at Rabbit Lake in the eastern Athabasca Basin marked the beginning of renewed activity in the province. Within seven years, numerous other deposits were discovered and Rabbit Lake was in production. With the discovery in the 1980s, of the world's highest grade uranium deposits, McArthur River and Cigar Lake, the Athabasca Basin was established as the premier uranium exploration district in the world.

History

The serendipitous discovery of pitchblende during the gold rush in the early 1930s, around Goldfields on the north shore of Lake Athabasca, established a new focus in the exploration sector in Saskatchewan that would remain for the rest of the century. In 1935, prospectors of the Mineral Locators Syndicate identified pitchblende at the Nicholson property, 3 km east of Goldfields. The prospectors were familiar with the mineral by virtue of their experience at the Port Radium radium mine on Great Bear Lake. Samples were collected by Geological Survey of Canada geologist F.J. Alcock and positively identified as pitchblende by GSC mineralogist H.V. Ellsworth (Alcock, 1936a). In the 70 years that followed, particularly in the post-war era, fluctuations in uranium exploration have been in response to changes in metal prices, security of contracts and government policy.

Recognition of the military significance of uranium led, in 1942, to reopening, at the request of the federal government, of the Eldorado Gold Mines Ltd. radium mine at Port Radium on Great Bear Lake in the Northwest

Table 7 – Saskatchewan potash producers.

Operator	Mine location	Type of mine	Capacity, tonnes per annum (tpa) K_2O equivalent
Agrium, Inc	Vanscoy	Underground	1 110 000
IMC Kalium, a business unit of IMC Global Inc	Belle Plaine	Solution	1 780 000
IMC Kalium	Esterhazy (K-1 & K-2)[1]	Underground	2 325 000
IMC Kalium	Colonsay	Underground	930 000
Potash Corp of Saskatchewan Inc. (PCS)	Patience Lake	Underground - converted to solution mining following 1986 flooding	630 000
PCS	Rocanville	Underground	1 400 000
PCS	Allan	Underground	1 150 000
PCS	Lanigan	Underground	2 335 000
PCS	Cory	Underground	830 000

[1] IMC Kalium is the 75% owner and manager of the K-1 and K-2 mines; the remaining 25% interest isheld by Potash Corporation of Saskatchewan.

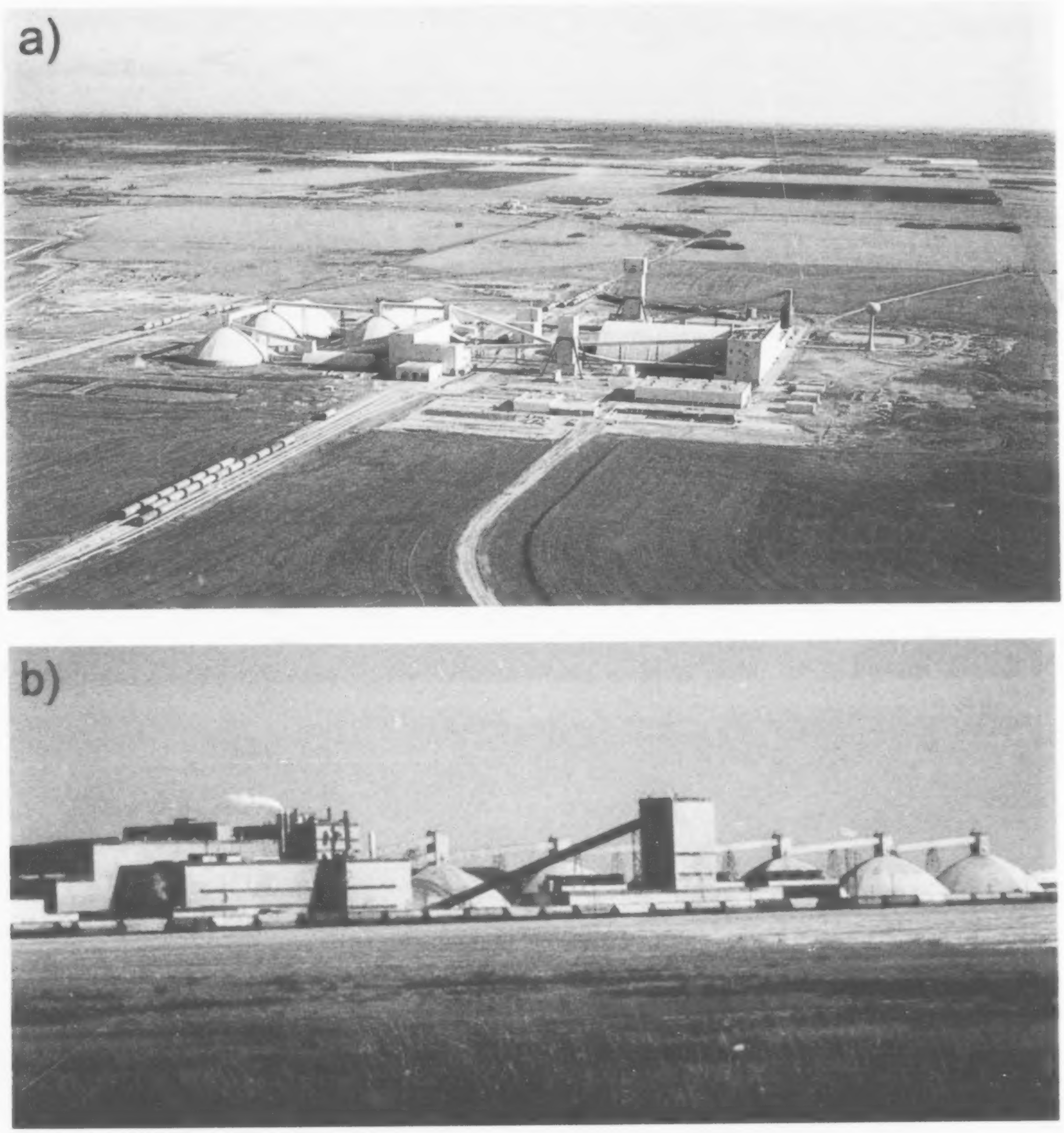


Figure 47 – a) Aerial view of the Cory underground potash mine operation (Potash Corporation of Saskatchewan Inc.). b) Panoramic view of the Belle Plaine solution potash mine (IMC Kalium Inc.).

Territories and the company's radium refinery at Port Hope, Ontario. The objective, however, was to mine and process uranium. At this time, the company was renamed Eldorado Mining and Refining Ltd. There followed, in 1943, a ban on the staking and mining of radioactive minerals by the private sector and, in 1944, expropriation of Eldorado by the federal government. Eldorado, as a crown corporation, held the sole exploration rights for radioactive minerals and that year began an intensive effort to find and develop new sources of uranium. The Great Bear Lake deposit, the Nicholson occurrence on the north shore of Lake Athabasca, and an unconfirmed occurrence near Lake Superior were then the only known locations of uranium minerals in Canada. Eldorado was assisted by the Geological Survey of Canada and, in September 1944, R. Murphy, exploration manager of Eldorado, and A.W. Joliffe of the

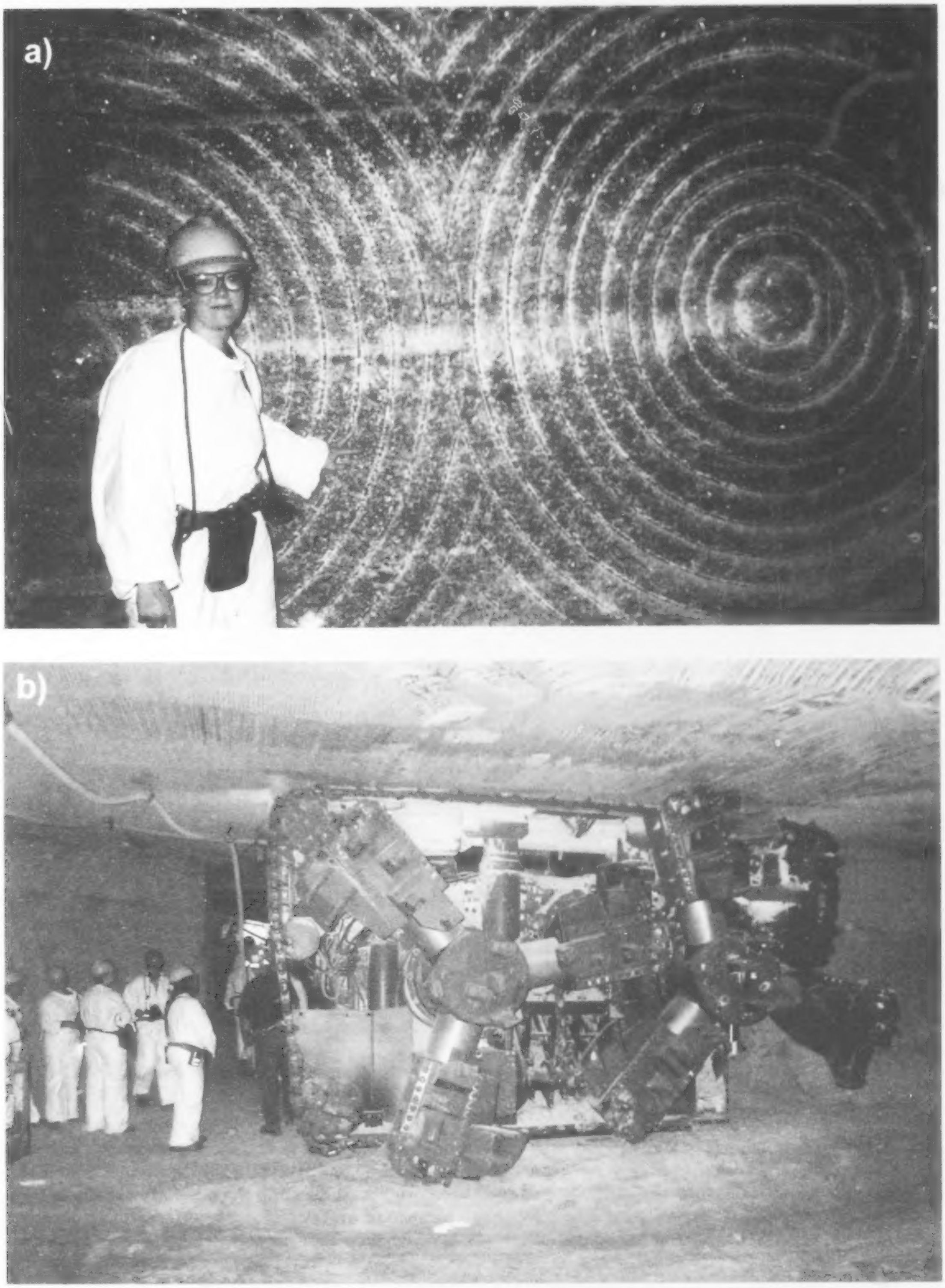
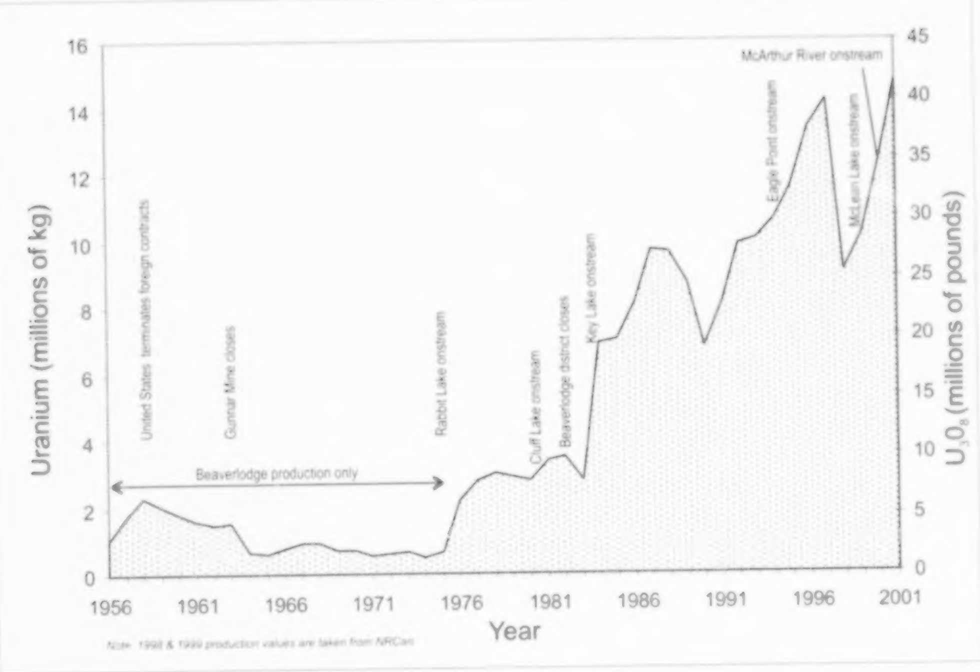


Figure 48 – a) Fresh mining cut, showing score marks left by continuous mining machine. b) Underground mining machine.



Note: 1998 & 1999 production values are taken from NRCan

Figure 49 – Uranium production in Saskatchewan, 1956-2001.

GSC examined the Nicholson showing and recommended prospecting and staking in the area.

Using Geiger counters, prospectors found more than 1000 pitchblende showings during the 1945 field season, in what became known as the Beaverlodge region, and the town of Goldfields was reactivated. On September 27, 1946, Philip St. Louis discovered pitchblende near a well-expressed fault at Ace Lake. Subsequent development of this showing led to definition of the Ace and Fay orebodies.

In 1948, lifting of the ban on private staking resulted in one of the largest staking rushes in Canadian history. Within 5 years, the Ace-Fay-Verna mine was in production, more than 200 companies were active in the district, and some 1000 new occurrences of pitchblende had been discovered. Veteran prospectors Walter Blair and Albert Zeemel, working for Gilbert Labine, then President of Gunnar Gold Mines Ltd., discovered radioactive boulders in muskeg on the south end of Crackingstone Peninsula. This discovery led to the development of the Gunnar mine, the second largest in the camp next to Ace-Fay-Verna.

After extensive diamond-drilling and sinking of the Ace shaft, plans for production from the Ace-Fay orebodies were announced in March 1949 and subsequently realized in 1953. The settlement of Beaverlodge, Eldorado's base, became established in 1949 and the town of Uranium City followed in 1952. Electric power for this development was obtained from the Wellington Lake hydroelectric plant, installed by Cominco in 1939 to service the Box mine at Goldfields.

The exploration boom that started in 1948 lasted until 1958, and the following year, 1959, was the peak production year for the camp. The cancellation of all foreign contracts by the United States in that year, in favour of developing American domestic resources, spelled the demise of the Beaverlodge district. By 1964, Eldorado remained the only uranium producer in Saskatchewan, surviving with the aid of a federal subsidy and stockpiling program, and by reducing production capacity.

The Ace-Fay-Verna mine was the first to open, in 1953, and last to close, in 1981. In the intervening years, some 36 deposits across the camp had been advanced to the underground development stage, and a total of 16 mines had been put into production, utilizing three separate milling facilities. The Eldorado and Gunnar mills were supplied with ore from their own deposits, although Eldorado also undertook some custom milling. The Lorado mill relied mostly on custom milling.

The ebb in mineral exploration prompted the Saskatchewan Government to introduce a financial assistance program to companies with approved exploration work schedules. In 1967, a consortium named the Dynamic Group, taking advantage of this program, conducted a systematic airborne radiometric survey of the unexplored Athabasca Basin. Subsequent to the survey, the Group reached agreement with the British American Oil Company (Gulf Oil Company), whereby Gulf acquired five permits held by the Group covering high-priority anomalies and the airborne survey data. The cost was an undivided 20% interest in all lands optioned by Gulf from the Group and in any future lands acquired by Gulf in northern Saskatchewan. In October 1968, as a result of following up airborne anomalies in the Wollaston Lake area, Gulf drilled the first hole into the Rabbit Lake deposit and obtained one of the richest intersections found to that time, an impressive 0.5% U over 59.4 m.

The Rabbit Lake discovery, together with improving forecasts for uranium demand, precipitated a land staking rush unequalled at the time in Canadian mineral-exploration history. During the fiscal year ending March 31, 1969, a total of 12 918 170 ha (31,896,718 acres) was acquired under the Mineral Disposition Regulations, 1961. In addition to the 625 051 ha (1,543,336 acres) acquired through ordinary staking procedures, 12 293 119 ha (30,353,382 acres) were acquired under 169 prospecting permits. Also, a first for Canadian mineral exploration was the nature of the companies engaged in this rush: most were oil rather than mining companies. Land was acquired as permits covering thousands of square kilometres following the oil-industry style. Traditional mining companies, however, moved more slowly, unaccustomed to this approach.

When Gulf acquired the Dynamic Group permits, Mokta (Canada) Ltd., a subsidiary of Compagnie de Mokta, which had been exploring in Canada since 1963 and Saskatchewan since 1964, sent a team to investigate airborne radiometric anomalies in the Carswell Dome area. Initially attracted to the Beaverlodge region, Mokta soon turned their attention toward the Athabasca Basin, undoubtedly prompted by their experience with sandstone-hosted uranium deposits in Gabon, West Africa. Investigations in the Cluff Lake area in 1969 resulted in discovery of the D orebody, which was of extremely high grade, and of the N, OP, R and Claude deposits during the next few years.

By late 1972, the exploration rush was over and exploration permits were dropped or reduced to mineral leases and claim blocks. Although proving fruitless for many participants, work undertaken at this time provided clues that would lead to other major uranium deposits, notably Midwest Lake.

In 1974, a joint-venture group headed by Uranerz Exploration and Mining Ltd. approached the Saskatchewan Government, proposing an exploration partnership. The offer was accepted and the Saskatchewan Mining Development Corporation (now Cameco Corporation) was born on June 4, 1974. Exploration by the group produced, in 1975, the Key Lake Gaertner orebody and, in 1976, the Deilmann orebody along strike from the Gaertner.

Beginning in 1974, great strides were made by the Saskatchewan Geological Survey, financed under a Canada-Saskatchewan agreement, in geological mapping of the Shield and in interpretation of its evolution. Mapping of the Highrock Lake area by G.E. Ray in 1976 and 1977 showed that the Key Lake deposits are hosted at the unconformity between graphitic gneisses in the metamorphic basement and the overlying Athabasca Group. It quickly became apparent that a little-known deposit, the Collins Bay A zone, discovered by Gulf in 1971, shared a similar relationship. The role of 'graphitic basement horizons', recognizable as electromagnetic conductors, in controlling the locations of unconformity-type uranium deposits became established as an exploration concept.

This concept led to re-evaluation of the Collins Bay A zone (1976) and discovery of the West Bear deposit (1977) and Collins Bay B zone (1977) by Gulf. Imperial Oil Ltd. (Esso Minerals Canada Ltd.) and joint-venture partners, Numac Oil and Gas Ltd. and Bow Valley Industries Ltd., had cause to review the significance of the Midwest Lake uraniferous boulder train found by prospectors in 1969. The Athabasca boulders that made up the train overlay an indicated basement conductive zone beneath Athabasca sediments estimated to be up to 300 m thick. Drilling in 1977 showed low-grade mineralization at the Athabasca Group–basement unconformity and, in 1978, an economic orebody was outlined.

The Midwest discovery illustrated that deeper parts of the basin could be successfully explored, in contrast to previous successes, which were confined to the margins. It also led to general acceptance and implementation of the Key Lake exploration model. Thus, by 1978, much of the open ground in the Athabasca Basin was staked and exploration expenditures rose, reaching a peak of around $100 million in 1980.

Several significant discoveries followed in the eastern part of the basin: the Collins Bay D zone (1977), Dawn Lake 11 and 14 zones (1978), McClean Lake (1979), Eagle Point North and South deposits (1980), Cigar Lake (1981), Jeb (1982), Sue zones (1988) and McArthur River or P2 North (1989). Most of these deposits lack a diagnostic surface expression of mineralization, such as boulders, and were outlined by systematic drilling of electromagnetic conductors defined by airborne and follow-up ground surveys. During this period, the Dominique-Peter (1982), Dominique-Janine (1984), P Patch (1986), and Anne and Colette (1994) deposits were located within the Carswell Structure in the western part of the basin, and several occurrences of unconformity-type uranium were also discovered along the north shore of Lake Athabasca. Despite these exploration successes, the level of activity fell consistently throughout the 1980s in response to the massive decline in uranium prices, from more than US$40/lb. U_3O_8 in 1979 to less than US$10/lb. U_3O_8 in 1990.

The uranium production industry was influenced by a number of major events in the 1970s and 1980s. Rabbit Lake came on stream in October of 1975 and reached planned annual production levels of around 2000 t of uranium (t U) or 5.2 million lb. U_3O_8 in 1977. Production decreased in 1981 due to depletion of the higher grade portions of the ore zone, and the body was mined out by May 1984, although processing continued until October 1985, yielding 15 750 t U (41 million lb. U_3O_8) from 6 million t of ore. The mill was closed from July 1989 to August 1991, when it began to process ore from a series of small satellite orebodies and the Eagle Point underground mine. The Collins Bay B zone achieved first production in November 1985 and was mined out by February 1991.

Underground test mining of the Eagle Point deposit started in June 1991, and definition drilling continued until 1993. Mining commenced in 1994 and continued until it was suspended on March 31, 1999, leaving 7308 t U (19 million lb. U_3O_8) in the ground for future production. Preparations for mining the two remaining Collins Bay satellite deposits, both of which lay beneath the waters of Collins Bay, started with the building of a dyke around the Collins Bay D deposit in the fall of 1994. Mining began late in 1995 and was finished by spring 1996, when the open pit was decommissioned. The dyke around the Collins Bay A deposit was completed in spring 1996; mining started at year's end and was completed by the middle of 1997. Stockpiled ore from both deposits was blended with Eagle Point ore to provide the mill feed.

COGEMA Resources Inc. started development of the McClean Lake deposits (Jeb and Sue A, B, C and CQ) in 1995 with mine-site construction. Initial mining was from the Jeb deposit, which was mined out in 1997, with the ore being stockpiled for processing at the McClean mill. Meanwhile, the Sue C pit was under development and commenced production in 1998. Final approval to use the Jeb open pit as a tailings-management facility were received in 1999. The mill started processing stockpiled ore in June 1999 and yellowcake shipments began in August. The annual production limit was raised from 2308 t U (6 million lb. U_3O_8) to 3077 t U (8 million lb. U_3O_8) in 2001, and the evaluation of a new deposit (Sue E) started.

Production at Cluff Lake began from the small, high-grade D zone open pit in the summer of 1979, and was completed by 1980, although milling of stockpiled ore continued until 1984. A second phase of mining and milling of the basement-hosted, lower grade ore began in 1983 with production from the OP (1983-1985) and Dominique-Peter (1985-2000) underground mines, and from the Claude open pit (depleted by 1989). Following this, a new open pit, known as Dominique–Janine North, operated from 1990 to 1991. Uranium production at Cluff Lake was supplemented by production from other, shorter lived deposits, including the Dominique–Janine South extension open pit (1994-1997), Dominique–Janine South underground mine (1996-2000), West Dominique–Janine underground mine (1999-2002) and West Dominique–Janine West extension underground mine (2000-2002). After 1999, only the higher grade portions of the deposits were mined. COGEMA has also reprocessed Phase 1 tailings, which contained recoverable uranium and 8090 oz. of gold. Production ceased in 2002.

In 1982, Eldorado Nuclear Ltd. shut down its operation at Beaverlodge, bringing to a close all production from the Uranium City area. Eldorado, however, acquired the assets of Gulf Minerals Canada Ltd., Gulf Canada Ltd. and Uranerz Canada Ltd., in effect the ownership of the Rabbit Lake mine-mill complex and the related properties. In 1988, Eldorado and the Saskatchewan Mining Development Corporation, owned respectively by the federal and provincial governments, were amalgamated to form Cameco Corporation, the world's largest uranium production and marketing company. The corporation presently commands 60% of the identified uranium reserves of the Athabasca Basin, and owns uranium refining and conversion facilities at Blind River and Port Hope, Ontario. Also held are interests in historic and potential future uranium, gold and other mineral-production and -exploration properties in Saskatchewan, Canada and overseas.

The Key Lake Mining Corporation, replaced by a Cameco Corporation (66.67%)–Uranerz Exploration and Mining Ltd. (33.33%) partnership and later by a Cameco Corporation (83.333%)–COGEMA Resources Inc.–(16.66%) partnership, commenced production from the Key Lake orebodies by open-pit mining in 1983. The production rate, in excess of 5000 t U annually, made this mine the world's largest uranium producer at that time. The Gaertner orebody was mined out by 1986 and mining of the Deilmann orebody began subsequently. In 1991, the milestone production of 100 million lb. U_3O_8 (38 465 t U) was reached. Annual production of between 5000 and 5500 t U continued until 1998, when 5385 t U (14 million lb. U_3O_8) were produced from stockpiled ore. The last ore from the Deilmann open pit was mined in April 1997, at which time the pit was converted to a tailings-management facility. The mill was shut down at the end of June 1999 for refitting to handle blended ore from the remaining stockpile and the new McArthur River deposit, 80 km to the northeast.

The uranium ore bodies at Rabbit Lake, Key Lake and Cluff Lake were mined by conventional open-pit and underground methods. The more recently discovered deposits, such as McArthur River, Midwest Lake and Cigar Lake, all of which are high grade and deeply buried beneath sediments of the Athabasca Basin, have required development of innovative underground-mining methods during test-mining programs.

At Midwest Lake (originally operated by Denison Mines Ltd. and now operated by majority partner COGEMA Resources Inc.), underground test mining was carried out between 1988 and October 1989. A 185 m shaft was sunk and a level driven above the orebody. Two blind boreholes, 1.2 m in diameter, were drilled to sample the orebody and test this technique as a mining method. Although there has been no activity since, government approval was given in 1998 to mine the deposit using a nonentry, jet-boring method, with the ore being milled at the McClean mill.

The Cigar Lake Mining Corporation (in 2001, a partnership between Cameco Corporation [50.025%], COGEMA Resources Inc.[37.100%], Idemitsu Uranium Exploration Canada Ltd.[7.875%] and TEPCO Resources Inc. [5%]) was established to manage the development of the giant Cigar Lake deposit, at present the second largest undeveloped high-grade uranium deposit in the world. The corporation undertook test mining between 1990 and 1993, sinking a 500 m shaft and developing two levels, one above the orebody at 420 m and the other below it at 480 m. The upper level was abandoned due to poor ground conditions. On the lower level, two novel mining methods, boxhole boring and jet boring, were successfully tested in a part of the orebody that had been prefrozen to ensure integrity of the excavated area. In 1993, after mining 113 t of ore grading 13.2% U (15.6% U_3O_8) by jet boring, and 53 t of ore grading 14.7% U (17.3% U_3O_8) by boxhole boring, the mine was placed on care-and-maintenance until 1997. In 1997, joint federal-provincial approval was obtained to proceed with development of the orebody. A second phase of test mining commenced, which lasted until the end of 2000 and included the trial of a 5.2 m diameter reaming machine and prototype freeze-hole drill. In 2000, it was agreed that the lower grade ore could be mined and processed 43% at the McClean Lake mill and 57% at the Rabbit Lake mill. Waste would be placed in the mined-out and converted Sue C pit. Cameco became operator of the program in 2001. Engineering design and preparation of licensing applications are underway. Start-up is targeted for 2006, and a new proposal is currently under review to process all mine concentrate at Rabbit Lake, with the resultant yellow-cake product proportioned as originally agreed for further milling.

Development of the McArthur River orebody, the largest high-grade uranium deposit in the world, was initiated in 1993 by Cameco with the completion of a headframe and 200 m shaft. Atomic Energy Control Board (AECB) approval for construction of the mine was given early in 1997, and the Joint Federal-Provincial Uranium Review Panel and government approvals followed in February and May. In 1998, surface facilities, a second shaft and underground workings were all under development and the road to Key Lake was completed. In 1999, with completion of the No. 2 shaft, surface facilities, and freeze-hole drilling around the initial mining area, and the No. 3 shaft underway, mine commissioning commenced. The first ore was reamed and processing started in December 1999. Underground development of the 530, 560 and 640 m levels proceeded in 2000, and the first shipment of slurried ore was delivered to the Key Lake mill in January. Tailings are stored in the converted Deilmann pit.

Uranium exploration has remained active during the past decade, and has resulted in several recent discoveries in the Athabasca Basin. In 1992, COGEMA discovered the Shea Creek deposit, at the sub-Athabasca unconformity at a depth of 705 m, about 20 km south of the Cluff Lake mine site. In the eastern part of the basin, new discoveries were made in 2000 by Cameco at La Rocque Lake, approximately 30 km north-northwest of the Midwest Lake deposit, and by JNR Resources Inc. in the Moore Lakes area, about 30 km south of McArthur River.

In 2002, some 34 years after the discovery at Rabbit Lake, the Athabasca Basin continues to be the premier uranium-exploration district in the world. Expenditures are projected to be just under $16 million in 2002, an increase of just over 10% from 2001 (Figure 41). There is currently aggressive mine-site exploration at Cluff Lake, McClean Lake and Rabbit Lake. Reconnaissance exploration is focused on advancing deep geophysical targets associated with major basement structures below the eastern part of the basin. Industry leaders Cameco Corporation and COGEMA Resources Inc. account for most of the work, but more than a dozen companies are currently active. In November 2002, Cameco announced the Millennium zone discovery on its joint-venture Cree Extension Project, including an intersection of 4.28% U_3O_8 over 30.3 m. To the east, JNR Resources continues to evaluate numerous uranium occurrences on the Moore Lakes property. In 2002, seven drillholes were completed on the Maverick zone, with the best intersection in hole ML-25 of 0.62% U_3O_8 over 9.1 m, including 1.2% U_3O_8 over 4.8 m.

Athabasca Basin

Uranium deposits spatially related to the sub–Athabasca Group unconformity, and referred to as unconformity-type, were first discovered in 1968 at Rabbit Lake and have been the world's premier uranium exploration target ever since, because of their characteristic high grade. The Athabasca Group is an unmetamorphosed, fluvial and marine clastic sequence dominated by quartz sandstones and deposited in Paleo- to Mesoproterozoic times (ca. 1700 Ma). The group covers an area of approximately 100 000 km^2 and is up to 1400 m thick.

The deposits occur mainly, although not exclusively, in a northeast-trending belt near the eastern margin of the basin (*Mineral Resource Map of Saskatchewan*, back pocket). Cluff Lake, on the west side of the basin, is a significant past-producer and thus underscores the potential of other areas in the basin.

Major discoveries in Saskatchewan span a 20-year period, starting in 1968 (Table 8). Discovery costs (per kg U in 1985 dollars) between 1971 and 1983 have been estimated at $1.53 in Saskatchewan compared with $13.58 in the remainder of Canada. A total of 383 800 t U was found during this period with a expenditure of $588 million. Since 1983, discovery of the Sue zones at McClean Lake and the McArthur River P2 North deposit have kept the discovery cost at less than $2.00/kg U. Development of existing and new production facilities has kept apace of the new discoveries.

A model for the new unconformity-type uranium deposits was developed in the 1970s (Figure 50). The highest grade ore straddles the unconformity, although mineralization may extend a few hundred metres above and below it. There is a clear spatial association with graphitic rocks in the underlying metamorphic basement, and most ore deposits are associated with major structures (Figure 51); fault-bounded, perched ore zones occur at many deposits, and displacement of the sub-Athabasca contact by several tens of metres is evident at numerous deposits. Both reverse and normal faults appear to have been influential in the genesis of the deposits.

The unconformity-type uranium deposits are extremely high grade, a full order of magnitude greater than all other deposit types, with ore grade in excess of 10% at the two richest mines in the world, Cigar Lake and McArthur River. There is general consensus that mixing of oxidized supergene fluids and reduced basement fluids is largely responsible for metal deposition at the unconformity, as first proposed by Knipping (1974). Models evolved for efficient transport of uranium cations in solution, and effective fixing of uranium metal at redox fronts (cf. Ruzicka, 1993). The role of precursor 'proto-ore' in basement graphitic gneiss, in contributing to the high grades via recurring remobilization and concentration of uranium along major structures, has been advanced in recent exploration models (e.g., Wheatley *et al.*, 1996).

Unconformity deposits are marked by a complex mineralogy and geochemistry. Pitchblende,uraninite and coffinite are the primary uranium minerals, accompanied by pararammelsbergite, rammelsbergite, niccolite, gersdorffite, millerite, carrollite, molybdenite, various copper sulphides, clausthalite, galena, sphalerite, hematite, goethite, psilomelane, and native copper and gold. Geochemically, uranium is accompanied by Ni, Co, Mo, Cu, Pb, Zn, Mn, Fe, V, Ag, Au, Pt-group elements, S, Se and As (e.g., Hoeve and Sibbald, 1978a). In some deposits, the diversity of minerals and concentration of elements associated with uranium are low, whereas, in others, many different mineral phases are present and elements are associated with uranium in potentially economic quantities (e.g., gold at Cluff Lake, nickel at Key Lake, copper at Dawn Lake). Gangue minerals include quartz, calcite, dolomite, ankerite, siderite, chlorite, sericite and adularia.

Deposits are surrounded by extensive alteration envelopes that penetrate both the Athabasca Group and the crystalline basement. This alteration is distinct from that of the lateritic weathering profile in the uppermost basement, and from low-temperature, diagenetic mineral assemblages in Athabasca Group sandstone (Hoeve *et al.*, 1980). Hydrothermal alteration is variously marked by chloritization, tourmalinization, hematization (several episodes), illitization, silicification and dolomitization (e.g., Hoeve, 1984). Other features include the destruction of graphite, corrosion of quartz and formation of residual clay seams and caps above mineralization in the Athabasca Group, bleaching (removal of hematite), and euhedral quartz-, siderite-, pyrite- and hematite-filled fractures.

Geochronology of the ore deposits is complex (e.g., Cumming and Krstic, 1992). Based on basin-wide synthesis of U-Pb data, the oldest mineralizing event occurred at McArthur River ca. 1514 Ma, with evidence for mineralizing fluids ca. 1330 to 1380 Ma at all deposits, and evidence for secondary enrichment and/or remobilization events throughout the basin deposits at ca. 1280, 1000, 575 and 225 Ma. The earliest known mineral deposition at McArthur River is some 200 to 300 m.y. after the inferred deposition of the Athabasca Group.

Cigar Lake Deposit

Geology: The deposit is characterized by its immense size, stratigraphic position entirely within the Athabasca Group sandstones, presence of very high grade massive mineralization and an extensive and intense clay-alteration envelope. The 2150 m long, east-striking orebody is about 430 m below surface and lies directly over a well-defined basement ridge, or bump (Figure 52). The richer eastern part of the orebody is up to 100 m wide and 20 m thick. Host rocks are microconglomeratic Manitou Falls Formation sandstones. The basement ridge, interpreted as a mylonite zone, is composed of augen-textured graphite- and sulphide-bearing sillimanite-cordierite-garnet pelitic gneiss.

Table 8 – Major unconformity-type uranium deposits in Saskatchewan.

Map no.[1]	Deposit	Ownership (operator first)	Share (%)	Discovery date	Reserves & resour-ces (t U)	Grade (% U)	Athabasca thickness (m)	Basement rock types	Depth of mineraliz-ation (m)	Remarks
U 44	Rabbit Lake	Cameco Corporation	100.0	1968	15 769[2]	0.27	Absent (eroded)	Meta-arkose, plagioclasite (in part graphitic), calc-silicate dolomitic marble, granite segregation, pegmatite, microgranite	0–200	In hanging wall of Rabbit Lake thrust fault; subcrop below drift, mineralized boulder train; **mined out**
U 43	Collins Bay A	Cameco Corporation	100.0	1971	65 002	4.82	Absent (eroded)	Pelitic graphitic gneiss, granite-segregation pegmatite in contact with granitoid gneiss	5–20	In clay zone at Athabasca Group unconformity in hanging wall of Collins Bay thrust fault; subcrop below drift, mineralized boulder train; **mined out**
U 43	Collins Bay B	Cameco Corporation	100.0	1977	15 750[2]	0.61	25	Pelitic graphitic gneiss, granite segregation pegmatite in contact with granitoid gneiss	05–300	Dominantly in Athabasca Group in footwall of Collins Bay thrust fault; **undeveloped**
U 43	Collins Bay D	Cameco Corporation	100.0	1979	21 502	1.86	-	Pelitic graphitic gneiss, granite segregation pegmatite	-	Adjacent to Collins Bay thrust fault; **mined out**
U 45	Raven	UEX Corporation	100.0	1972	3 650	0.12	Absent (eroded)	Sillimanite quartzite, calcareous meta-arkose, psammopelitic gneiss	0–300	Fracture-controlled mineralization in altered basement; **undeveloped**
U 45	Horseshoe	UEX Corporation	100.0	1974	1 550	0.14	Absent (eroded)	Sillimanite quartzite	60–300	Fracture-controlled mineralization in altered basement; **undeveloped**
U 42	Eagle Point	Cameco Corporation	100.0	1980	24 750[1] (8 603)	1.3 1.1	Absent (eroded)	Pelitic-psammopelitic gneiss (in part graphitic), quartzite, granite segregation pegmatite	0–460	In hanging wall of Collins Bay thrust fault, structurally controlled in altered basement; operations suspended; **re-opened in 2002 on 3 yr. Reserves**
U 25	Fond-du-Lac	Fond-du-Lac First Nation	100.0	1967	400	0.2	30	Meta-arkose, pelitic gneiss (occasionally graphitic)	100–300	Mineralization in Athabasca Group, subcrop below drift, mineralized boulder train; **undeveloped**
U 49	West Bear	UEX Corporation	100.0	1977	450	0.37	-	Pelitic graphitic gneiss	170–400	Mineralization occurs at unconformity; **undeveloped**
U 38	Midwest	COGEMA Resources Inc. Redstone Resources Inc. Tenwest Uranium Ltd. OURD (Canada) Co. Ltd.	54.8 20.7 20.0 4.5	1978	13 755	3.8	200	Pelitic graphitic gneiss locally with garnet, granite segregation pegmatite, bounded by granitoid gneiss; cross-cutting diabase dikes	0–300	Dominantly at sub-Athabasca Group unconformity; mineralization extends more than 100 m below unconformity and to surface (source of mineralized boulder train); **undeveloped**
U 39	Dawn Lake (11, 11A, 11B and 14 zones)	Cameco Corporation COGEMA Resources Inc. JCU (Canada) Expln. Co. KEPCO Resources America Ltd.	58.000 20.115 19.000 2.885	1978	4 977	1.43	100	Pelitic graphitic gneiss, calc-silicate, granite-segregation pegmatite	30–200	Mineralization extends 50 m above and 100 m below the sub-Athabasca Group unconformity; no surface expression; **undeveloped**
U 41	McClean Lake: North McClean Lake: South	COGEMA Resources Inc. Denison Mines Ltd. OURD (Canada) Co. Ltd.	70.0 22.5 7.5	1979 1980	5 077	1.79	150	Pelitic graphitic gneiss, granite-segregation pegmatite	130–180 11–240	Mineralization extends above and below sub-Athabasca Group unconformity; **undeveloped**
U 40	McClean Lake: JEB	COGEMA Resources Inc. Denison Mines Ltd. OURD (Canada) Co. Ltd.	70.0 22.5 7.5	1982	400	0.45	100		85–120	No surface expression; mined out, pit in use as tailings management facility; **mined out**

Table 8 (continued)

Map no.[1]	Deposit	Ownership (operator first)	Share (%)	Discov-ery date	Reserves & resour-ces (t U)	Grade (% U)	Athabasca thickness (m)	Basement rock types	Depth of mineraliz-ation (m)	Remarks
U 41	McClean Lake: Sue A, B, C and D zones)	COGEMA Resources Inc. Denison Mines Ltd. OURD (Canada) Co. Ltd.	70.0 22.5 7.5	1988	10 117	1.36	50–80		8–165	No surface expression of these zones; **mining suspended in 2002**
U 53	Key Lake	Cameco Corporation COGEMA Resources Inc.	83.333 16.667	1975	75 600[2]	2.45		Graphitic pelitic gneiss adjacent to granitoid gneiss massif	50–150	Mineralization extends above and below sub–Athabasca Group unconformity but predominantly within 20 m below unconformity; subcrop below drift; mineralized fluvioglacial boulder train; **mined out**
U 47	Cigar Lake	Cameco Corporation COGEMA Resources Inc. Idemitsu Uranium Exploration Canada Ltd. TEPCO Resources Inc.	50.025 37.100 7.875 5.000	1981	89 076 45 620	15.44 14.35	410–450	Graphitic pelitic gneiss, minor calc-silicate, granite-segregation pegmatite	±440	Mineralization predominantly in lens at sub–Athabasca Group unconformity; some fracture–controlled mineralization above and below unconformity; no surface expression; **start-up targeted for 2006**
U 21	Maurice Bay	Cameco Corporation UEM	66.67 33.33	1977	600	0.5	1–130	Pelitic gneiss (in part graphitic), minor quartzite and amphibioite	0–150	Mineralization in three zones: B and Main in Athabasca Group and A in basement; subcrop below drift; mineralized boulder train; **undeveloped**
U 36	Cluff Lake D	COGEMA Resources Inc.	100.0	1969	43 702	3.41	–	Pelitic to psammopelitic gneiss (in part graphitic; Peter River Gneiss)	0–35	Mineralization in Athabasca Group sandstones and siltstones at thrust fault-inverted unconformity; mineralized boulder train; subcrop; **mined out**
	Cluff Lake:	COGEMA Resources Inc.	100.0					Quartzofeldspathic gneiss (Earl River Gneiss), granite pegmatite		
U 35	Claude o/p			1969						**Mined out**
U 36	Dominique-Peter u/g[4]			1982						**Mined out**
U 36	Dominique-Janine (N) o/p[5]			1984						**Mined out**
U 36	Dominique-Janine (S) o/p ext.			1989						**Mined out**
U 36	Dominique-Janine (S) u/g			1991						**Mined out**
U 36	West Dominique–Janine u/g			1996	(1 654)	2.2				**Mined out**
U 36	West Dominique–Janine (W) ext.			2000						**Mined out**
	Cluff Lake (other deposits)				22 000[3]	0.5	–	Pelitic to psammopelitic gneiss (in part graphitic; Peter River Gneiss)	0–300	Fracture-controlled mineralization in altered basement; **mined out**
U 50	McArthur River (P2 North)	Cameco Corporation COGEMA Resources Inc.	69.805 30.195	1989	151 742 *55 924*	17.96 9.11	460–590	Pelitic graphitic gneiss–quartzite	±550	Mineralization in Athabasca Group underlying over–thrust basement wedge; **active**

[1] refers to *Mineral Resource Map of Saskatchewan*, back pocket

[2] actual production, now mined out

[3] original resources, now depleted by production

[4] underground mine

[5] open-pit mine

Reserves are unstandardized. 'Reserves' and 'Resources' use Cameco Corporation definitions for deposits where Cameco is the operator. Not all figures in the table may be exactly comparable. Only partial resources are presented. All figures shown are derived from Cameco Corporation and COGEMA Resources Inc. websites, annual reports and news releases. Figures in brackets represent remaining reserves.

The hydrothermal alteration envelope in basement rocks beneath the deposit is superimposed on previous retrograde and regolithic alteration, and is dominated by illite and chlorite and characterized by the development of dravite, phosphates and calcite. Concentrically zoned alteration in the sandstones around the deposit extends up to 300 m above. The alteration progresses outward from a zone of illitization, quartz dissolution and intense fracturing close to the orebody, through zones of euhedral quartz-crystal growth and grey alteration impregnated with sulphides, to an outer zone of bleaching. Above the orebody is a cap of hematized, massive illitic clay containing siderite and hydrocarbons.

The orebody itself is zoned. The massive high-grade core of pitchblende and Ni-Co arsenides is surrounded by a lower grade outer zone. Perched orebodies (Figure 52), which extend up steeply dipping faults, are attributed to late-stage remobilization. Three stages of mineralization are recognized. The first stage paragenesis consists of predominant pitchblende and uraninite with associated rammelsbergite, niccolite, gersdorffite, cobaltite, glaucodot, pyrite, marcasite and bravoite. Stage 2 mineralization is predominantly pitchblende with a wider range of associated primary and secondary arsenides, sulpharsenides and sulphides that, in addition to those listed for Stage 1, include smythite, chalcopyrite, bornite, digenite, chalcocite, covellite, galena, sphalerite, jordisite and clausthalite. Stage 3 mineralization is exclusively pitchblende and coffinite.

History and Production: The Cigar Lake deposit was discovered in 1981 by COGEMA Canada Ltd., operator of the Waterbury Lake joint venture of COGEMA, Saskatchewan Mining Development Corporation (SMDC), Idemitsu Exploration Canada Ltd. and Corona Grande Exploration Corporation. Delineation drilling of 170 holes had, by the end of 1985, outlined an estimated 150 000 t U (390 million lb. U_3O_8) at a grade of 8% U (9.4% U_3O_8). That year, ownership passed to the Cigar Lake Mining Corporation, which was formed by the original partners and which now consists of Cameco Corporation (50.025%), COGEMA Resources Inc. (37.100%, which includes wholly owned subsidiary Corona Grande [3.750%]), Idemitsu Uranium Exploration Canada Ltd. (7.875%) and TEPCO Resources Inc. (5%).

From 1982 to 1987, COGEMA completed a variety of geotechnical tests on the petrography, metallogeny and geochemistry of the ore, and submitted an application for a test-mining project, which received approval. Cameco sank the shaft to a depth of 501 m between 1988 and 1990, began developing the 420 m and 480 m levels, and constructed a water-treatment plant. Reserves were upgraded in 1991 to 148 000 t U (384.8 million lb. U_3O_8) grading 12% U (14% U_3O_8).

From 1991 to 1993, pilot-scale jet-boring and boxhole-boring mining methods were tried in frozen ground via two vertical 1.55 m holes bored up through the deposit from the 480 m level: 113 t of ore grading 13.2% U were extracted by jet boring and 53 t ore grading 14.7% U were mined by the boxhole method. The mine was then placed on care-and-maintenance until 1997, when a second phase of test mining commenced to try a new mine-development system using a 5.2 m diameter

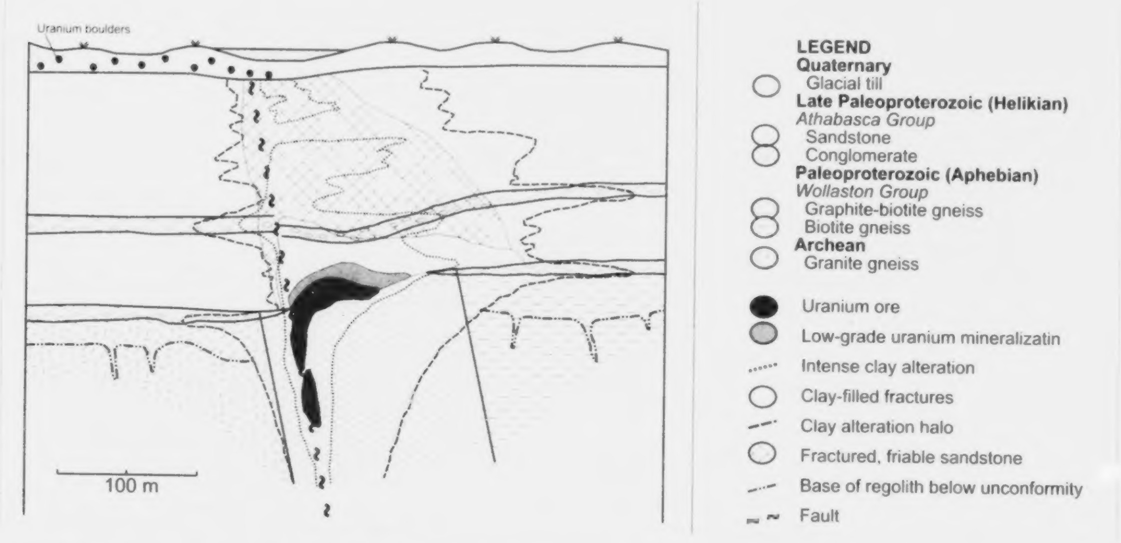

Uranium boulders
100 m
LEGEND
Quaternary
○ Glacial till
Late Paleoproterozoic (Helikian)
Athabasca Group
○ Sandstone
○ Conglomerate
Paleoproterozoic (Aphebian)
Wollaston Group
○ Graphite-biotite gneiss
○ Biotite gneiss
Archean
○ Granite gneiss
● Uranium ore
● Low-grade uranium mineralizatin
Intense clay alteration
○ Clay-filled fractures
Clay alteration halo
○ Fractured, friable sandstone
Base of regolith below unconformity
Fault

Figure 50 – Schematic summary of the historical model for unconformity-type uranium deposits, developed by J. Hoeve and T. Sibbald through the early 1970s (from Sibbald, 1985).

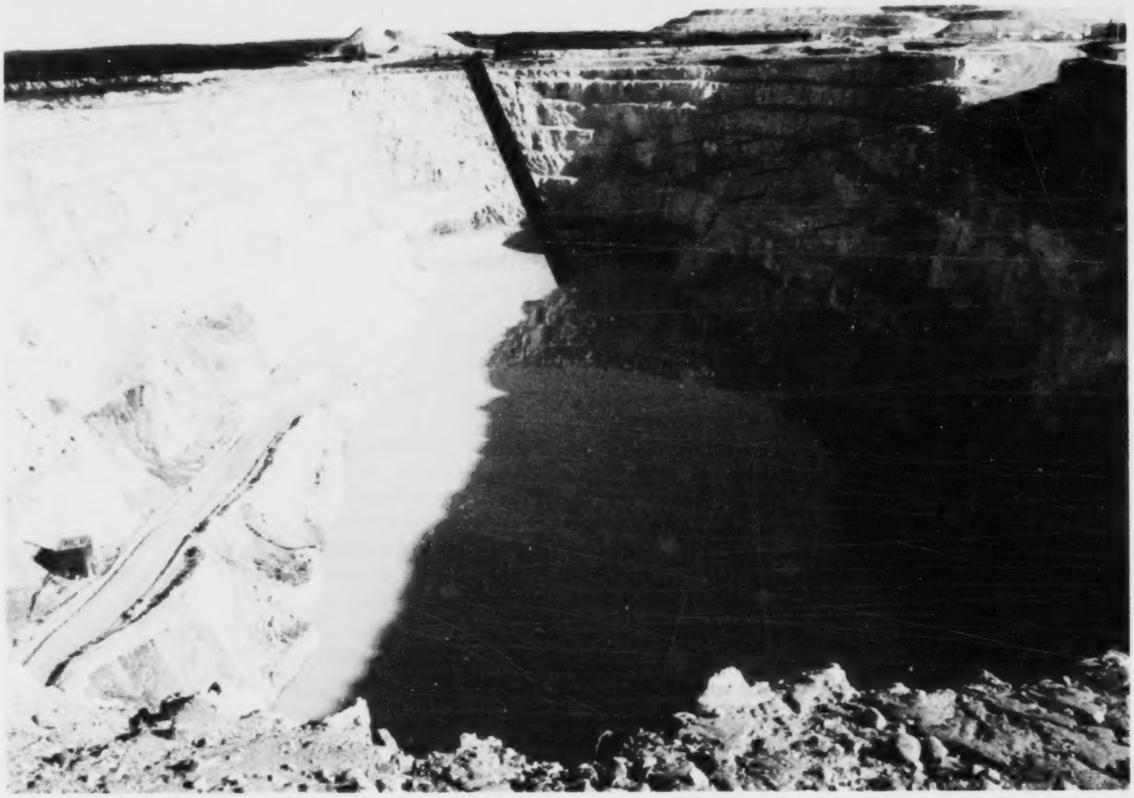


Figure 51 – View of the Sue C pit, McClean Lake operation, northeastern Athabasca Basin, looking north along the strike of the main structure that localizes uranium ore. Photo taken in August, 2002. Solid line is the fault trace, heavy dashed line is the unconformity on top of the Paleoproterozoic Wollaston Supergroup pelitic gneiss (dark), and short thin lines within the light-coloured rock are bed-form traces within Athabasca Group quartzite above the unconformity.

reaming machine and a prototype freeze-hole drill. By 2000, reserves were estimated to be 142 320 t U (370 million lb. U_3O_8) at a head grade of 11.5% U (13.6% U_3O_8). Test mining was completed by year's end. In 2001, total proven and probable reserves were 89 076 t U (231.6 million lb. U_3O_8) grading 15.44% U (18.21% U_3O_8), and total inferred resources were estimated to be 45 620 t U (118.6 million lb. U_3O_8) grading 14.35% U (16.92% U_3O_8). Licensing applications for engineering design and preparation were underway, although mining was not expected to start until 2006.

Cluff Lake Mine

Geology: The Cluff Lake mine is in the western part of the Athabasca Basin, near the southern margin of the basement core of the circular Carswell Structure, considered to be of meteorite-impact origin. The core is surrounded by successive, 4 to 5 km wide rings of deformed and fragmented Athabasca Group sandstones, mudstones and stromatolitic dolomite. The basement rocks principally comprise granitoid gneisses (Earl River Complex) and metasedimentary gneisses (Peter River Gneisses), invaded by sheets of pink, leucocratic, garnetiferous granite–granite pegmatite. The geology of the mined deposits is given below.

The ***D zone*** is located in an overthrust block at the inverted sub-Athabasca unconformity, which dips moderately northward. Graphitic Peter River gneisses overlie interbedded siltstones, conglomerates and sandstones of the Athabasca Group. Massive ore occurred mainly in the siltstones and in the superjacent basement close to a mylonite. The orebody yielded 4370 t U from 128 000 t of ore grading 3.41% U. It was ellipsoidal, measuring about 140 m long, up to 25 m wide and 7 m thick, with mineralization forming discontinuous lenses. Pitchblende, uraninite and coffinite ore minerals were associated with gold and gold tellurides; native selenium and lead; bismuth, nickel and cobalt arsenides; jordisite; pyrite; galena; and chalcopyrite. Hydrocarbon buttons and other carbonaceous material also occurred in the ore. Ore emplacement was accompanied by perva-

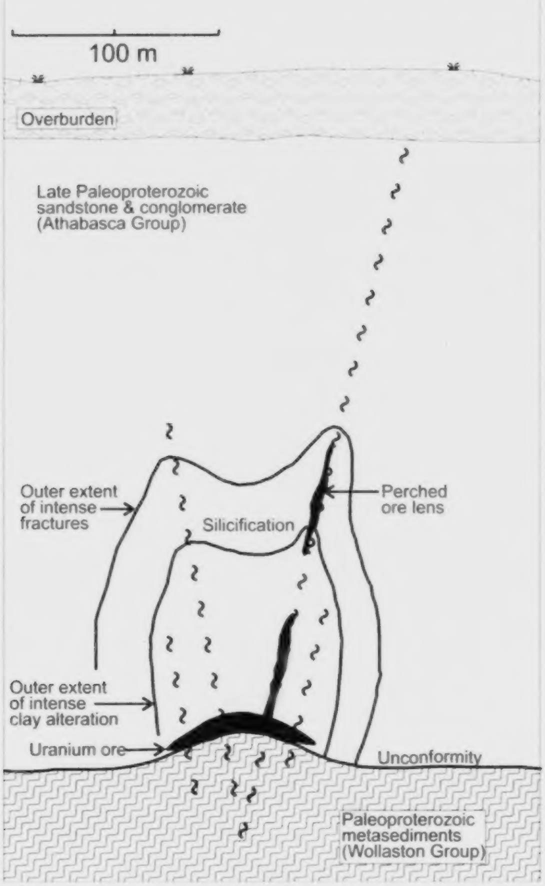

100 m
Overburden
Late Paleoproterozoic sandstone & conglomerate (Athabasca Group)
Outer extent of intense fractures
Silicification
Perched ore lens
Outer extent of intense clay alteration
Uranium ore
Unconformity
Paleoproterozoic metasediments (Wollaston Group)

Figure 52 – Schematic diagram of the general structural setting of the Cigar Lake uranium deposit (**after **Thomas** et **al., 2000).

sive hydrothermal alteration, affecting both the basement and the Athabasca Group.

The ***Claude deposit*** occurred within Peter River gneisses, in part graphitic and interlayered with granitoids. For the most part, mineralization was localized within an east-trending subvertical shear zone containing rotated fault blocks, although northeast-trending faults were also mineralized. The deposit was approximately 600 m long and 200 m wide, and had a maximum thickness of 90 m. Mineralization comprised uraninite and coffinite, in association with minor clausthalite, galena, pyrite, chalcopyrite, sphalerite, jordisite, covellite and hydrocarbon buttons. Alteration, distinguished by hematization and chloritization-argillization, was intimately associated with the mineralization, which typically developed at the redox interface, marked by hematized and pale green, bleached rock.

The ***OP deposit*** comprised 1) fracture-controlled mineralization at the intersection of two thrust faults, dipping gently to the north and north-northwest, that superimposed unaltered Peter River gneisses over Athabasca Group, the paleoweathered basement (regolith) and other basement gneisses; and 2) to the east, discontinuous mineralization in subvertical, northerly-trending fractures, partially filled with vein quartz, cutting Peter River gneisses. The mineralization comprised uraninite with chalcopyrite, galena, clausthalite and pyrite, all deposited on quartz crystals. Minor coffinite and associated Mg-chlorite were also present. Alteration zones around the veins were very narrow.

The ***Dominique-Peter deposit*** occurred entirely within the basement close to a mylonite zone marking the contact of the Peter River and Earl River gneisses. These gneisses are cut by three sets of faults, all of which displace the mylonite zone. Mineralization occurred as fracture fillings, veinlets and disseminations typically within tens of metres of the mylonite zone, mainly in the north- and east-northeast-trending faults that cut Peter River gneisses and mylonite. Two mineralization assemblages were observed: a uraninite–polymetallic-sulphide assemblage and a uraninite–dravite–simple-sulphide assemblage. The Dominique-Peter orebody was estimated to contain 11 600 t U in 1 761 000 t of ore grading 0.66% U.

The geological environment of the ***Dominique-Janine North deposit*** resembles that of Dominique-Peter. The contact between the Peter River and Earl River gneisses is fault controlled and crosscut by the subvertical, northerly-trending main ore structures. Mineralization was present within these structures where they were intersected by steep, northwest-dipping faults. Regolith and small blocks of Athabasca Group occurred in the open pit, illustrating the proximity of the sub-Athabasca unconformity. The deposit had estimated reserves of 874 t U in ore grading 0.38% U.

The ***Dominique-Janine South deposit*** was discovered by drilling in 1986, and later drilling indicated it to be of higher grade than Dominique-Janine North. It contained estimated reserves of 5 510 t U in ore grading 0.58% U. The northern part of this new deposit was hosted by basement gneisses, as was the Dominique-Janine North deposit, whereas the southern part was unconformity-type mineralization, like the much higher grade D zone deposit.

History and Production: The Cluff Lake deposits, formerly owned by Amok Ltd. (80%) and Cameco Corporation (20%), later by COGEMA Resources Inc. (80%) and Corona Grande Exploration Corporation (20%; a wholly owned subsidiary of COGEMA Resources Inc.), are now owned outright by COGEMA Resources Inc. The deposits were mined out in 2002. They occurred at or near the southern edge of the uplifted basement core of the Carswell meteorite-impact structure, within the western part of the Athabasca Basin. Uranium mineralization was first discovered in 1968, as a result of follow-up work to an airborne radiometric survey that had revealed several weak anomalies. Significant zones of mineralization discovered include the D, N and OP deposits in 1969-1970; the Claude in 1971; the Dominique-Peter in 1981; the Dominique-Janine in 1984; and the West Dominique-Janine in 1996. The zones outcropped or subcropped below glacial drift and gave rise to geochemical dispersion haloes, which were detectable by ground and, in some cases, airborne surveys. The Shea Creek prospect, a zone of weak uranium mineralization associated with a group of strong, deep EM conductors, lies outside the Carswell Structure some 20 km south of the Cluff Lake deposits. Shea Creek was discovered in 1992 and is still being assessed. High-grade stratabound lenses of authigenic xenotime containing high concentrations of rare-earth elements occur locally in nearby Athabasca Group rocks.

The Cluff Lake deposits were originally estimated to contain in excess of 20 000 t U, the grade of the ore varying substantially in different deposits. The D zone, for example, had an average grade of around 3.5% U, whereas the others graded around 0.5% U. Mining of the deposits commenced with the high-grade D zone, and continued with the lower grade zones.

Phase I open-pit mining of the D zone took place in 1979 and 1980, although milling of the ore began in May 1980 and continued until 1984, with uranium-bearing gravimetric tails from this phase being processed between May 1983 and August 1984. Gold, residually concentrated in the leach tailings derived from Phase I processing of the gravimetric concentrate from D zone ore, was extracted in 1987 and 1988; production was 8090 oz. of gold. Phase II operations were initiated in 1983 with development of the Claude deposit open pit and the OP underground mine. Production from these deposits began in August 1984. Depletion of the OP orebody in 1985 was followed by production from the Dominique-Peter underground mine, which lasted until 2000. Closure of the Claude open pit, in June 1989, was followed immediately by production from the Dominique-Janine North open pit, which was mined out by December 1991. Subsequently, mining of the Dominique-Janine South extension open pit and underground mine lasted from 1994 to 1997 and from 1996 to 2000, respectively. Production from West Dominique-Janine deposit, where underground mining started in 1999, ended in May 2002. Full mine reclamation is underway. Ore will be processed through 2003, when final shut down of the entire mining and milling operation will occur.

Key Lake Mine

Geology: The Key Lake deposits, on the southeastern margin of the Athabasca Basin, are mined out. The orebodies were long and narrow, and separated by a 'gap' of approximately 1 km, where glacial erosion had penetrated below the Athabasca Group into the underlying basement. The more northerly Deilmann deposit exceeded 900 m in length, varied in width from 30 to 50 m, and was about 40 m thick; the Gaertner deposit was about 800 m long, 10 to 50 m wide and 60 m thick. Both deposits were underlain by Early Proterozoic graphitic metasediments, which mantle Archean granite-gneiss domes. Both groups of rocks are overlain unconformably by the Athabasca Group, which comprises basal conglomerates grading upward into sandstones. Mineralization occurs where a northeast-trending reverse fault, showing a vertical displacement of 30 m, intersects the sub-Athabasca unconformity.

In the ***Gaertner deposit***, the hanging wall of the fault comprised sillimanite-cordierite-graphite gneisses of the main graphite zone, which contained up to 30% graphite and 3% pyrite. Mineralization was hosted, as veins, massive nodules and disseminations, largely by down-faulted Athabasca Group sandstones that are extensively fractured, quartz corroded and clay altered. Some mineralization extended for a distance of 30 m into the underlying basement, which consists of altered, mylonitized, folded and brecciated biotite gneisses.

The ***Deilmann deposit*** was the most recently developed. Fracture-controlled ore zones in the crystalline basement thickened upward to the unconformity, where massive ore occurred. The east-northeast-trending basement fractures gave rise to mineralized 'roots' extending more than 100 m down dip. Some mineralization occurred in graphitic gneisses; however, ore shoots were characteristically in adjacent biotite gneisses. Perched ore bodies occurred in the Athabasca Group sandstones, and disjointed satellite orebodies were present at the unconformity where it was intersected by crossfaults.

The main ore minerals were pitchblende and coffinite, accompanied by nickel arsenides, sulpharsenides and sulphides. Cobalt, molybdenum, lead, zinc, copper, gold and silver were present as minor constituents of the ore. Attempts to recover the nickel were unsuccessful.

History and Production: The Key Lake deposits were originally owned jointly by Cameco Corporation (66.67%) and Uranerz Exploration and Mining Ltd. (33.33%), later solely by Cameco, and finally by Cameco (83.333%) and COGEMA Resources Inc. (16.667%). The deposits were discovered in 1975 by a combination of airborne radiometrics, mineralized boulder prospecting, and geophysical and geochemical surveys. The initial clue was a uranium anomaly in lake water, identified in 1969 but not followed up. Uranerz geologists, on visiting the anomaly area in late 1971, found high-grade pitchblende boulders derived by fluvioglacial erosion of the Gaertner orebody. These boulders were traced to source and drilling eventually identified *in situ* mineralization. The two orebodies, Gaertner and Deilmann, and a zone of mineralized overburden were identified. Grade was about 2% U, with substantial associated concentrations of nickel, cobalt and arsenic. Initially estimated reserves were approximately 75 600 t U, of which 23 900 t U grading 3% U were attributed to the Gaertner orebody and 45 900 t U grading 2.4% U to the Deilmann orebody. A small proportion of reserves, 5800 t U grading 0.6% U, occurred as 'cobble ore' (glacial deposits in which mineralized boulders were sufficiently concentrated to form ore). Open-pit mining began in 1981, and first production of yellowcake was achieved in October 1983 at an annual rate of 4600 t U. After 1985, production exceeded nominal mill capacity, reaching a new high of 5452 t U in 1993. Extraction from the Gaertner pit was completed in 1986 and production from the Deilmann pit started in 1989. Mining of the last part of the Deilmann orebody was completed in April 1997, and the open pit was converted to a tailings-management facility to hold the McArthur River tailings. Milling ceased in July 1999 and the mill was converted to process ore from the McArthur River deposit.

McArthur River (P2 North) Mine (Figure 53)

Geology: The main structural ore control at McArthur River is the southeast-dipping P2N reverse fault that has thrust hanging-wall Paleoproterozoic rocks (including graphitic metasediments) upward by more than 80 m into the younger Athabasca Group sandstone (Figure 54). The mineralization is concentrated at the fault contact between the Athabasca Group and the Paleoproterozoic basement rocks over a strike distance of 1700 m. Exploration drilling from the 550 m level has defined two mineralized pods. Pod 1 occurs at the basement-sandstone contact. Pod 2, referred to as the 'pelite mineralization', is deeper and occurs in metasedimentary basement rocks that overlie a quartzite unit. Only one of the exploration drillholes from surface cut the pelite mineralization. Ore in sandstone, fault zone or pelitic gneiss below the unconformity locally reaches grades of 59.4% U (70% U_3O_8).

The ore consists of an older generation (ca. 1308 Ma) of massive, botryoidal uraninite filling fractures and vugs, associated with pyrite, chalcopyrite, covellite, chalcocite, galena and hydrocarbon-bearing buttons. This older mineralization shows a gradational replacement by a younger episode (ca. 586 Ma) of uraninite and galena mineralization. There is no significant Ni-Co association. Alteration is dominated by intense silicification, whereas a well-developed clay alteration halo (a common feature of other unconformity-type uranium deposits) is practically absent. Chloritization and dravitization are more strongly developed in the footwall sandstones. Basement alteration, which is more intense in the hanging wall, consists of illitization and chloritization accompanied by the development of dravite, apatite and carbonate.

History and Production: Cameco Corporation discovered the deposit in 1988, then delineated it by surface drilling through to 1992. The mine is now owned by Cameco (69.805%; as operator) and COGEMA Resources Inc. (30.195%), having previously passed through various joint ownerships that included Uranerz Exploration and Mining Ltd., AGIP Resources Ltd., Interuranium Canada Ltd. and Imperial Metals Corporation.

McArthur River, now the largest and richest uranium mine in the world, was confirmed as a major high-grade deposit by 1990. The preliminary reserve estimate was 77 000 t U (200 million lb. U_3O_8) grading 3.4% U (4% U_3O_8). In 1992, the reserve estimate was increased by 30% to 100 000 t U (260 million lb. U_3O_8) at 4.24% U (5% U_3O_8). After underground exploration was approved in February 1993, the headframe was completed by July and the shaft had reached a depth of 200 m in late October. By 1994, underground exploration to define the limits of the orebody and reserves was underway. A 5.5 m diameter shaft was completed to the 550 m level and the 530 m level was being developed in basement. The following year, a 140 m long crosscut was driven west from the shaft, and a drill drift was developed in hanging-wall basement rocks, parallel to the northeast-trending thrust fault, to test the deposit over a 300 m strike length with a 10 000 m diamond-drilling program. By 1996, the geological reserves stood at 160 000 t U (416 million lb. U_3O_8) at an impressive grade of 12.7% U (15% U_3O_8). This included proven mineable reserves of 72 700 t U (189 million lb. U_3O_8) in 457 000 t of ore at a grade of 15.9% U (18.8% U_3O_8) and an additional resource of 87 600 t U (227.8 million lb. U_3O_8).

In 1997, the AECB gave approval for construction and the Joint Federal-Provincial Uranium Review Panel recommended approval of the project to the Saskatchewan and federal governments, who gave their approvals in May. Surface facilities, a second shaft and underground workings on the 530 and 640 m levels were extensively developed in 1998 (Figure 53). By then, reserves had been upgraded to 98 160 t U (255.2 million lb. U_3O_8) at a grade of 14.7% U (17.33% U_3O_8) and resources to 87 600 t U (227.8 million lb. U_3O_8) at a grade of 10.2% U (12.03% U_3O_8). Combined reserves and resources amounted to 185 784 t U (483 million lb. U_3O_8) at a grade of 11.9% U (14.03% U_3O_8).

In 1999, surface facilities were completed in September, freeze-hole drilling was completed around the initial mining area and the freezing system was operating.

Figure 53 – Panoramic view of the McArthur River mine complex.

The No. 2 shaft was completed and the No. 3 shaft was underway. Reaming of the first ore took place on December 6, processing started December 7, and the first delivery of slurried ore to the Key Lake mill was made in January 2000. Underground development on the 530, 560 and 640 m levels took place in 2000. Proven and probable reserves in 2001 were quoted as 151 742 t U (394.5 million lb. U_3O_8) at a grade of 17.96% U (21.18% U_3O_8).

McClean Lake Mine

Geology: The McClean Lake uranium deposits comprise the McClean North and South zones, the Sue A, B, C, D and E deposits, and the Jeb deposit. All of the deposits straddle the sub-Athabasca unconformity, but only the Jeb and Sue C deposits have been mined.

The ***Sue deposits*** lie about 3 km east of the McClean North and South deposits, along a north-northeast-striking fault line known as the Sue trend. From north to south, the five deposits are Sue B, A, C, D and E. The Sue trend lies along the western flank of the Archean Collins Bay granitic dome, where it is thrust up against Paleoproterozoic Wollaston Supergroup silicified and graphitic paragneisses. The Sue A and B deposits occur at the unconformity atop a thin (<20 m), near-vertical unit of graphitic gneiss at the fault contact with the Archean granite. The Sue C, D and E deposits lie below the unconformity within silicified and graphitic paragneiss adjacent to a splay fault 100 m east of the granitic dome. The Sue C (including the adjacent CQ and CQQ deposits) is similar to McArthur River and Eagle Point mineralization, and consists of high-grade (4.5% U or 5.3% U_3O_8), low Ni-As vein-type mineralization. Mineralization comprises massive uraninite, pitchblende, minor coffinite, and very minor associated Ni, As, Pb, V, Mo, Cu and Co minerals.

The ***Jeb deposit***, located 10 km north of the McClean Lake and Sue deposits, consisted of a southeast-plunging, fault-controlled pod of uranium mineralization, 122 m long by 50 m wide by 7 to 17 m thick. The deposit, which is located over a local 'hump' in the basement and unconformity, straddles the unconformity. Basement-hosted ore consisted of low-grade remobilized material within graphitic pelitic gneisses and higher grade mineralization at the unconformity. Athabasca Group–hosted ore consisted of fracture-hosted primary pitchblende and lower grade remobilized material within the first 5 m of hematized and chloritized sandstones above the unconformity. The ore consisted mainly of pitchblende and nickel arsenides.

History and Production: The first significant mineralization, the McClean North zone, was discovered by a

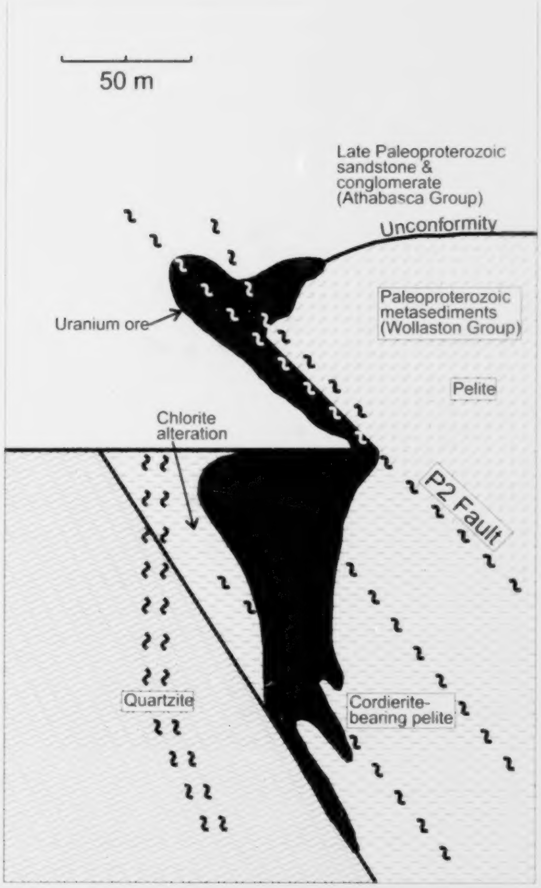

50 m
Late Paleoproterozoic sandstone & conglomerate (Athabasca Group)
Unconformity
Uranium ore
Paleoproterozoic metasediments (Wollaston Group)
Pelite
Chlorite alteration
P2 Fault
Quartzite
Cordierite-bearing pelite

Figure 54 – Schematic diagram of the general structural setting of the McArthur River deposit (after Thomas et al., 2000).

Canadian Occidental Petroleum Ltd. (CanOxy)–Inco Ltd. joint venture in 1979. Follow-up geophysical exploration and drilling led to the discovery of the McClean South zone in January of the following year. Delineation drilling (426 holes) determined combined reserves in McClean North and South to be 5385 t U (14 million lb. U_3O_8) in 353 802 t of ore grading 1.53% U (1.8% U_3O_8). Grades up to 23.6% U (27.8% U_3O_8) over 10 m were encountered.

The Jeb deposit was discovered by CanOxy in May 1982 during follow-up drilling of airborne radiometric and ground Max-Min anomalies. Ownership passed through a CanOxy-Canico joint venture and then Minatco Co. Ltd./Ltée. to the present COGEMA Resources Inc.–Denison Mines Ltd.–OURD (Canada) Co. Ltd. partnership. Definition drilling of the small orebody was completed by 1989. Surface stripping of the Jeb pit started in late 1994 and mining had reached a depth of 40 m by September. The deposit was mined out by 1997, the ore being stockpiled for eventual processing at the McClean Lake mill.

The Sue deposits were discovered between 1988 and 1991 by a CanOxy–Inco–Total Minatco Company Ltd./Ltée. joint venture, which conducted ground geophysics and percussion drilling over the Sue Lake grid, starting in 1987. The Sue A and B deposits were discovered in 1988, followed by the Sue C in 1989, Sue D in 1990 and Sue E in 1991. Sue A and B were discovered by drilling conductors delineated by ground VLF-EM and HLEM (Max-Min) surveys. Sue C and CQ were discovered by drilling DC-resistivity and IP anomalies approximately 100 m away from conductors.

Minatco became sole owner in 1990, and later went into partnership with COGEMA Resources Inc. The McClean Lake, Sue and Jeb deposits are now jointly owned by COGEMA Resources Inc. (70%), Denison Mines Ltd. (22.5%) and OURD (Canada) Co. Ltd. (7.5%).

In 1992, published reserves for all McClean Lake area (Wolly Project) orebodies was 17 300 t U (45 million lb. U_3O_8) at a grade of 2.7% U (3.2% U_3O_8). Exploration drilling along the Sue trend continued through 1993, and by 1994 reserves were estimated to be 19 300 t U (50.2 million lb. U_3O_8) at a grade of 2.78% U (3.3% U_3O_8). The decision to develop the McClean Lake deposits at a cost of $250 million was announced in March 1995, and erection of the mill started in February 1996. Also, the Sue C open pit was under development. Construction of mine site and facilities was completed in 1997 and, in 1998, the AECB and Saskatchewan Environment and Resource Management (SERM) approved use of the 120 m deep Jeb pit as a tailings-storage facility. Construction of the filter and drain system at pit bottom and a horizontal drift and raise to bring water up to the surface treatment plant were completed by mid-November 1998. Stripping for the Sue C open pit reached ore by year end.

Milling of stockpiled ore began June 23, 1999 and the first barrel of yellowcake was produced by July 12, with shipments starting in late August. The Sue C1 pit was mined to a depth of 100 m in 2000, the stockpiled ore being sufficient to feed the mill for 1.5 years. The Sue C2 extension pit had reached a depth of 30 m in September. Officially opened on May 26, 2000, the mine's production limit was raised from 2308 t U (6.0 million lb. U_3O_8) to 3077 t U (8.0 million lb. U_3O_8) in 2001. Mining of the Sue C deposit ceased in 2002 (Figure 51), with the pit at a depth of 143 m and a total of 550 000 t of ore removed at an average grade of about 2% U. The McClean Lake mill has been expanded to receive ore from the Cigar Lake mine, targeted for start-up in 2006.

Midwest Deposit

Geology: The Midwest deposit lies beneath the Mink arm of South McMahon Lake. The orebody occurs at the sub-Athabasca Group unconformity above a narrow sequence of northeast-striking, steeply southeast-dipping Paleoproterozoic, partly graphitic garnetiferous pelitic gneisses, bounded on either side by granitic gneiss domes of presumed Archean age. A fault, adjacent and parallel to the pelitic gneisses, downthrows the unconformity 30 m to the west. The overlying 200 m of Athabasca Group consists of cross-bedded sandstones and minor conglomerate lenses. Diabase dykes cut both cover rocks and basement close by.

Discontinuous pods and lenses of mineralization occur over a strike length of 3 km, but the bulk of the deposit is within a zone 1400 m long, up to 110 m wide and 36 m thick. Ore extends over 100 m into the basement along shear and breccia zones. Alteration around the deposit is characterized by chloritization and sericitization in basement rocks, and by sericitization in the Athabasca Group. The mineralization comprises pitchblende associated with the Co-Ni arsenides and sulpharsenides notably gersdorffite, rammelsbergite-pararammelsbergite, niccolite, maucherite, safflorite and cobaltite and minor galena, sphalerite, chalcopyrite and marcasite.

History and Production: Esso Minerals (Canada) Ltd., (Imperial Oil Limited) made the discovery in 1978 during diamond drill follow-up to airborne and radiometric anomalies from a 1969 airborne survey. A further 90 holes were drilled to outline the deposit. From 1978 to 1981 Esso drilled over 488 holes to define the orebody and allow calculation of reserves. The Midwest Joint Venture (originally a PNC Exploration (Canada) Company Ltd.-Denison Mines Limited-Bow Valley Industries Limited-Uranerz Exploration and Mining Limited partnership) took control of the property in 1987. The Midwest Joint Venture partners are currently COGEMA Resources Inc., (54.8%), and Denison Ltd., wholly owned subsidiaries Redstone Resources Inc., (20.7%) and Tenwest Uranium Ltd., (20%), and OURD (Canada) Co. Ltd., (4.5%).

Underground test mining was completed 27th October 1989. In 1994 reserves stood at 13 800 t U (35.8 M lb U_3O_8). The property has been dormant from 1995 to present.

Rabbit Lake Mine

Geology: Rabbit Lake, on the eastern margin of the Athabasca Basin, was the first discovery of the new unconformity-type uranium deposits, and the first of the high-grade deposits to be put into production. In addition to Rabbit Lake, subsequent economic discoveries were made along strike to the northeast in the Collins Bay area and farther north at Eagle Point. Ore from these associated deposits has been processed at the Rabbit Lake mill. The geology of the mined deposits follows.

The ***Rabbit Lake deposit*** is hosted by Early Proterozoic metamorphic rocks of the sub-Athabasca basement, comprising interlayered meta-arkoses and calc-silicates in the hanging wall (upper gneisses), massive meta-arkose in the core of the ore zone, and plagioclasite (in part graphitic), calc-silicates and dolomitic marbles in the footwall. The hanging-wall gneisses are cut by subconcordant sheets of pink granite–granite pegmatite. The Rabbit Lake thrust fault, which underlies the deposit, dips 30° to the south-southeast and downthrows the Athabasca Group sandstones to the northwest by at least 75 m, to lie against the crystalline basement. An older, northeast-trending, steeply dipping fault bounds the ore zone to the southeast.The ore zone was elongated in a northeasterly direction and had the shape of a laterally flattened pipe, around 550 m long, up to 250 m wide, 200 m deep and tilted to the northwest. A high-grade core was surrounded by a lower grade envelope of mineralization. Host-rock alteration pervades and surrounds the orebody and is typified by Mg-chloritization, dolomitization, silicification, tourmalinization and hematization. Mineralization comprised several different generations of pitchblende and coffinite, accompanied by a broad suite of minerals that included euhedral quartz and dolomite, calcite, siderite, hematite, chlorite, adularia, sulphides, native copper and carbon buttons. Secondary uranium minerals, uranium mineral coatings and impregnations were also developed. On a large scale, mineralization was geochemically simple, comprising essentially uranium with only minor concentrations of the Ni, As, Co, Se, etc. that characterize many other unconformity-type deposits.

The Collins Bay area, situated some 10 km northeast of Rabbit Lake, is underlain by granitoid gneisses of probable Archean age, Early Proterozoic metasediments and Athabasca Group sandstones. The granitoid gneisses are overlain by the Athabasca Group, which is downthrown by the northeast-trending Collins Bay (thrust) Fault. Three principal ore zones, the A, B and D, were outlined along a 3 km mineralized trend.

The ***Collins Bay A zone*** comprised a uraniferous boulder train and *in situ* pod of high-grade uranium-nickel arsenide mineralization at the unconformity between Paleoproterozoic Wollaston Supergroup metasediments and basal units of the Athabasca Group. It was confined within a zone of imbricate faulting in a flexure of the Collins Bay thrust, where hanging-wall Wollaston Supergroup metasedimentary paragneisses (graphitic pelitic and quartzofeldspathic gneisses) abut footwall Athabasca Group that rests unconformably on Archean granitoid gneiss. The 46 m long, 40 m wide and 16 m thick mineralized pod was surrounded by a zone of intense illite clay alteration, mainly of the footwall Athabasca Group. The uranium ore consisted of two generations of sooty pitchblende, coffinite and kasolite, which were accompanied by rammelsbergite, nickeline, niccolite, galena and pyrite. The deposit contained significant amounts of cobalt, silver and gold. Grades were locally as high as 54% U (63.7% U_3O_8).

The ***Collins Bay B zone*** was confined, for the most part, to the footwall of the Collins Bay thrust, primarily within sandstones and conglomerates of the Athabasca Group, which unconformably overlie Archean granitoids. Some mineralization occurred in the hanging wall, formed by upthrown graphitic metasediments. The orebody, approximately 915 m long, 30 to 122 m wide and 30 m in average thickness, comprised a lens or group of lenses parallel to the strike of the thrust, which is northerly except at the north end of the orebody, where it turns into the regional northeasterly trend. Imbrication characterizes the north-trending segment of the fault.

Ore and associated minerals included pitchblende, coffinite, niccolite, rammelsbergite, gersdorffite, maucherite, bravoite, violarite, chalcopyrite and other copper sulphides. Pyrite, covellite, bornite, tennantite, millerite, polydymite and safflorite were present locally. Unlike the Rabbit Lake deposit, the Collins Bay B zone was geochemically complex and contained significant nickel and arsenic in association with uranium.

The ***Collins Bay D zone*** was similar in shape, structure and geochemistry to the A zone and high-grade north end of the B zone. The massive lens, which formed the orebody, occurred in the Collins Bay Fault beneath 7.6 m of water and as much as 23.5 m of overburden. The deposit had a strike length of more than 700 m, widths ranging from 8 to 40 m and was up to 46 m thick. The high-grade uranium and nickel-arsenide mineralization was hosted by highly altered Athabasca Group adjacent to the Collins Bay thrust. The uranium ore consisted of pitchblende and coffinite, plus associated gersdorffite, nickeline and galena, but had no significant gold or silver values.

The Eagle Point mine area, comprising the ***Eagle South*** and ***Eagle North*** deposits, is located under the northeast end of Collins Bay, 3.5 km northeast along strike from the Collins Bay B, D and A zones. The Eagle Point deposits consist of a series of moderately to steeply dipping tabular lenses, pods and veins within a 300 m sequence of folded and metamorphosed Paleoproterozoic basement rocks in the hanging wall of the Collins Bay thrust. The mineralization is hosted by the lowest graphitic unit of the Wollaston Supergroup, between 1.5 and 365 m from its contact with presumed Archean basement granitoid. The mineralization, which is mainly structurally controlled, consists of uraninite and pitchblende with only minor amounts of other minerals, including boltwoodite, coffinite, pyrite, galena, chalcopyrite, native copper, weeksite, uranophane, marcasite, bornite, covellite, digenite, bravoite and small sooty blebs and buttons of carbon. Moderately to strongly developed, illite-dominated and illite-chlorite-clay alteration, and hematization, surround the ore zones.

History and Production: Initially owned by Gulf Minerals Canada Ltd. and Uranerz Canada Ltd., the Rabbit Lake deposit and surrounding mineral properties were acquired by Eldorado Resources Ltd. in 1982, followed by joint ownership by Cameco Corporation (66.67%) and Uranerz Exploration and Mining Ltd. (33.33%). In 1998, Cameco obtained sole ownership of the mine. The Rabbit Lake deposit was discovered in 1968, during ground follow-up to an airborne radiometric survey that detected a uranium anomaly in radioactive glacial overburden. Subsequent work showed the deposit to be associated with a conductivity anomaly, low magnetic and gravity signatures, and lake-bottom sediment geochemical highs.

Stripping began in 1974 following a development drilling program, and the mill started up in 1975. Peak annual production reached 2056 t U (5.3 million lb. U_3O_8) from ore grading around 0.4% U. Mining was completed in 1984 and the pit was turned into a repository for mill tailings from the remaining stockpiled Rabbit Lake ore and ore from the new Collins Bay B zone. Total production from Rabbit Lake was 15 769 t U from ore averaging 0.27% U, and from initially estimated reserves of 17 300 t U.

The Collins Bay property was formerly owned by Gulf Minerals Canada Ltd., then Eldorado Nuclear Ltd., then a Cameco Corporation (66.67%)–Uranerz Exploration and Mining Ltd. (33.33%) joint venture, and currently by Cameco. The A zone was found in 1971 as a result of ground follow-up of airborne electromagnetic anomalies. A mineralized boulder train was discovered by prospectors and traced to source beneath the waters of Collins Bay. Drilling revealed high-grade uranium-nickel mineralization. In 1976, following the recognition of possible ore controls at Key Lake, the A zone was re-evaluated and the strike extension of the underlying electromagnetic trend further explored. Drilling led in 1977 to the B zone, some 2 km south of the A zone, and in 1979 to the D zone, situated between the A and B zones. Initial reserves were estimated at 6500 t U grading 4.82% U in the A zone, 15 769 t U grading 0.61% U in the B zone, and 2154 t U grading 1.86% U in the D zone. Mining of the B zone by open pit was undertaken between 1984 and 1991, first production being achieved in late 1985 and a significant proportion of reserves stockpiled. The last of the ore was milled in early 1994. The A and D zones were also mined by open-pit methods between 1995 and 1997 and between 1995 and 1996, respectively.

The Eagle Point deposits were discovered in February 1980 by Gulf Minerals Canada Ltd., during systematic drill testing of geophysical and geochemical anomalies along the Collins Bay thrust fault, 3.5 km northeast along strike from the Collins Bay deposits. The Eagle North deposit was originally held equally by Eldorado Resources Ltd., Noranda Exploration Co. Ltd. and Saskatchewan Mining Development Corporation, whereas the Eagle South deposit was wholly owned by Eldorado Resources. A program of definition drilling on both Eagle South (66 253 m in 284 holes) and Eagle North (47 260 m in 245 holes) was conducted between 1980 and 1986, by which time five zones of mineralization had been identified and defined. Test mining started in June 1991 and, by the end of July 1992, underground development included a 1400 m ramp reaching the 180 m level, drifts on the 120 and 180 m levels, and fresh air and exhaust raises. Mineable reserves at this time were calculated as 27 000 t U (70.2 million lb. U_3O_8) from 3.38 million t of ore grading 0.8% U, and geological reserves as 20 100 t U (52.2 million lb. U_3O_8) from 2.26 million t of ore grading 0.89% U. By the end of 1993, the mill test had processed 39 000 t ore averaging 1.47% U (1.73% U_3O_8) and 4% of the reserves were stockpiled. Regulatory approval was received in 1994 and mining of the 144 and O2 zones commenced. By 1997, an additional 3630 t U (8.0 million lb. U_3O_8) of mineable reserves had been discovered in the lower 144 zone between the 260 and 400 m levels. Mining operations were suspended on March 31, 1999, but started again in 2002, with 2 to 3 years of reserves (7308 t U or 19 million lb. U_3O_8).

Cameco Corporation announced the restart of its 100% owned Rabbit Lake uranium operation midway through 2002; discovered in 1968, the revitalized mine is now the longest running uranium operation in Saskatchewan.

Beaverlodge District

The Beaverlodge deposits are characterized by epigenetic pitchblende veins and disseminations, primarily in rocks of the metamorphic basement. Some veins are present in the unconformably overlying late Trans-Hudson red beds of the Martin Group, formed of unmetamorphosed immature clastics interbedded with alkali basalts. There appears to be a general spatial association between the outcrop of the Martin Group and the major deposits, although there is no unequivocal explanation of this relationship (Figure 55). Pitchblende is the chief ore mineral, and thorium and rare-earth elements are absent. Ore grades did not exceed 0.4% U and were commonly less than 0.2%.

The epigenetic deposits are divided into two groups (Beck, 1969): simple and complex mineralogy. In the former, which is the more common and exemplified by Eldorado's Ace-Fay-Verna ore zones, pitchblende is accompanied by coffinite, brannerite, nolanite, pyrite, chalcopyrite and galena. In the latter, illustrated by the Nicholson ore zones, pitchblende occurs with coffinite; thucholite; sulphides, arsenides and selenides of nickel, cobalt, copper, lead and zinc; native gold and silver; and platinum-group metals.

The complex deposits are mineralogically similar to those of the Athabasca Basin, and there is some evidence to suggest that they are also of similar age. If this is the case, they would be geologically 350 to 650 m.y. younger than the ca. 1750 Ma deposits of simple mineralogy with which they are spatially associated (cf. Cumming and Krstic, 1992; Koeppel, 1968).

The early generation of epigenetic pitchblende, in veins and as disseminations, exhibits a strong structural control, occurring in the fractured wallrocks of major faults. Deposits are often tabular and of large vertical and horizontal extent. Red hematitic alteration of wallrocks, accompanied by albitization and development of chlorite and calcite, is typical adjacent to early pitchblende veins, although it is of variable intensity.

Production from the Beaverlodge district from 1953 to 1982 came from a total of 16 mines (Table 9). Between the initial staking rush in 1948, and peak production for the camp some 10 years later in 1959, more than 200 companies were active in the camp, and more than 1000 pitchblende occurrences were known (Figure 55). By the time the camp closed in 1981, a total of 16 mines had been put into production and some 20 other properties had been advanced to the underground exploration stage. Beck (1969) provided a comprehensive summary of the mineral deposits in the camp. Output of the Eldorado Ace-Fay-Verna operation and the Gunnar mine account for more than 90% of the total production from the camp, and are therefore the only deposits described in the following section.

Ace-Fay-Verna Mine (Figure 56)

Geology: The Ace-Fay-Verna deposit occurred as sporadic zones of mineralization over a distance of 5 km adjacent to the St. Louis Fault, which strikes east-northeasterly and dips 50°S. The fault separates meta-argillite, chlorite-epidote rock and red-altered feldspar rock in the footwall from alaskitic granite and paragneiss, overlain unconformably by the downfaulted Martin Group, in the hanging wall.

The Ace-Fay zones were located in the footwall. Breccia-type ore zones occurred within 15 m of the fault and consisted of a matrix of pitchblende, quartz, calcite, chlorite and pyrite in feldspar rock and quartz. Vein-type ore zones were associated with fractures striking roughly parallel to the fault, and formed single or anastomosing bundles that included pitchblende, quartz, calcite, chlorite, pyrite and, locally, clausthalite and nolanite. The Ura ore zones in the hanging wall occurred in flat-lying shears above and below the uncon-

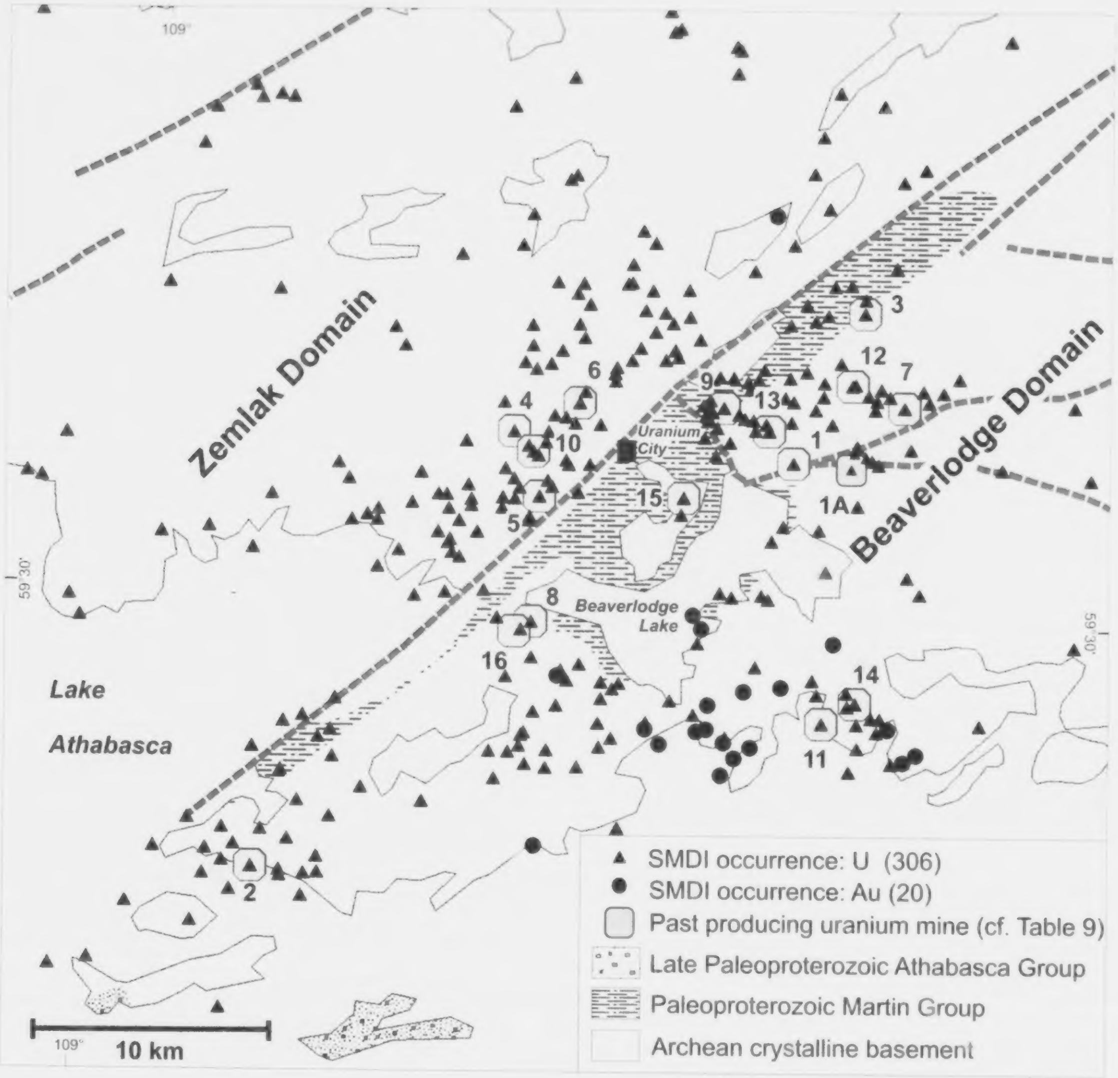

109°
Zemlak Domain
Beaverlodge Domain
Uranium City
Beaverlodge Lake
Lake Athabasca
59°30'
1
1A
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
10 km
SMDI occurrence: U (306)
SMDI occurrence: Au (20)
Past producing uranium mine (cf. Table 9)
Late Paleoproterozoic Athabasca Group
Paleoproterozoic Martin Group
Archean crystalline basement

Figure 55 – Location of all Saskatchewan Mineral Deposit Inventory occurrences in NTS area 74N with uranium or gold as the primary commodity. Geological details for the base map are available from the Geological Atlas of Saskatchewan (Slimmon, 2002; available online at www.gov.sk.ca/enermine/). Inset is from the historic synthesis of the Uranium City camp by Beck (1969), and shows the location of the 16 past-producing uranium mines (cf. Table 9).

formity separating the Martin Group from the underlying basement alaskite. Other ore zones occurred, in breccia and shears, in the alaskite and paragneiss. Wall rocks are impregnated and veined by hematite, epidote and quartz, especially in footwall meta-argillites.

The Verna zones occurred in a wedge-shaped mass of meta-argillite, hornblende schist and quartzite enclosed by alaskite granite in the hanging wall of the St. Louis Fault. Veins and stockworks of pitchblende included pink calcite and pyrite. White calcite and quartz occurred in barren and low-grade sections. Alteration was similar to that observed in the Ace-Fay deposit. The zones were tabular to lensoid and up to 25 m in width and 250 m in length.

History and Production: Eldorado began production in 1953 at some 450 t/day and, with enlargement of the plant, reached 1800 t/day by 1958. Maximum throughput achieved was 2100 t/day during the peak production period between 1958 and 1968, when annual yields ranged from 655 to 965 t U. The subsequent general decline in output was never significantly reversed, even

Table 9 – Total production from the 16 past-producers in the Uranium City camp. Numbers in left column refer to locations on Figure 55.

Map no.	Uranium mine	Production (t U)
1	Eldorado: Ace-Fay-Verna (1A)	16 035
2	Gunnar	6 892
3	Eldorado-Hab	763
4	Rix Smitty	436
5	Cinch Lake	285
6	Cayzor Athabasca	187
7	Eldorado-Dubyna	163
8	Lorado	89
9	Eldorado-Eagle	85
10	Rix Leonard	77
11	Nicholson	41
12	National Exploration	30
13	Nesbitt Labine	23
14	Eldorado–Fish Hook	15
15	Eldorado–Martin Lake	11
16	Uranium Ridge	10

though an expansion program was initiated in 1975. When the mine closed in 1982, annual output was around 385 t U.

The average grade of ore material was about 0.17% U through the peak production period and in excess of 0.25% U through a period of selective mining in the early 1970s. Mining was underground, utilizing three surface shafts and two internal winzes, and was carried out on 33 levels to a depth of around 1675 m. The mill, unlike most uranium mills in Saskatchewan, utilized a complex, energy-intensive carbonate leach as the main process; however, since the ore contained pyrite, there was also a more conventional acid-leach circuit.

Gunnar Mine (Figure 57)

Geology: The Gunnar deposit was hosted by a coarse-grained microcline-albite granite, the Gunnar granite, which is in contact with banded amphibolitic and quartzitic gneisses to the north. The granite comprises about 65% albite, 25% quartz, generally less than 5% potassium feldspar, and minor chlorite (after biotite) and muscovite. Within the granite, adjacent to the sedimentary-gneiss contact, there occur bodies of syenite, formed by albitization of the Gunnar granite. Individual bodies are up to 500 m long and 125 m wide. Calcite has locally replaced quartz, yielding a calcite syenite, similar to episyenites of the Massif Central of France. This rock, when leached, appears as a vuggy 'sponge rock'.

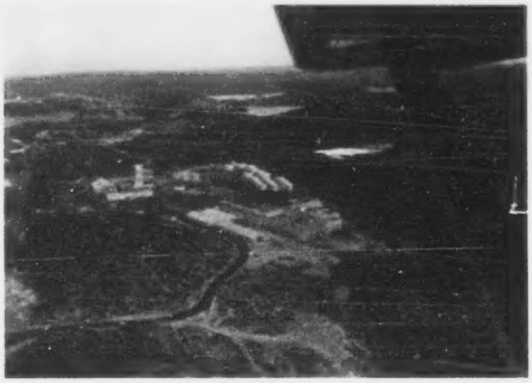


Figure 56 – Fay headframe and mill, Beaverlodge district, 1959 (courtesy of Saskatchewan Archives Board, Photo No. 59-322-36).

The orebody occurred in brecciated portions of the syenite. Pitchblende, together with small amounts of uranophane, rimmed albite and formed stringers, blebs and disseminated grains in the host rock. Gangue minerals were calcite, euhedral quartz, hematite, chlorite, kaolinite, pyrite, chalcopyrite and galena.

History and Production: Radioactive boulders around the Gunnar deposit were discovered in 1952. The pipe-like orebody, approximately 150 m in diameter, 300 m deep and plunging 45°SSE, was outlined by some 22 500 m of diamond drilling on a 22.5 m square grid pattern. The orebody was estimated to contain approximately 3.6 million t of ore grading 0.17% U. Production commenced in September 1955 and continued until the orebody became depleted in October 1963. Extraction was initially from open pit until 1958, from underground and open pit until October 1961 and then solely

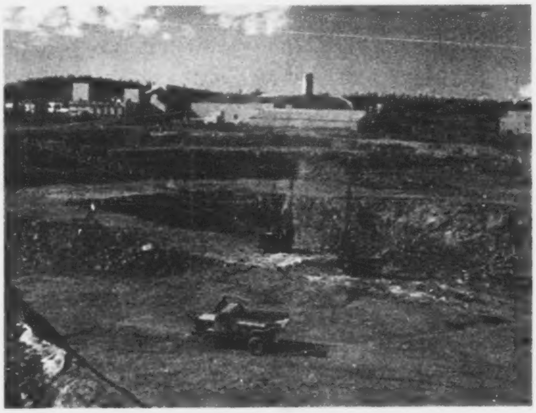


Figure 57 – Gunnar open pit and mill, Beaverlodge district, 1956 (courtesy of Saskatchewan Archives Board, Photo No. 56-305-62).

from underground. Some 5.0 million t of ore grading 0.148% U were milled.

Resources and Current Production

Saskatchewan continues to be the world leader in uranium, accounting for 100% of production in Canada in 2001, and about one-third of world production. Total Saskatchewan production was approximately 23.33 million t U_30_8 in 2001 (Table 10) from five operations, both underground and open pit (Figure 58), within the Athabasca Basin. Mining ceased at Cluff Lake in 2002, leaving McArthur River, McClean Lake and Rabbit Lake as the sole producers at year end. Milling of stockpiled ore will continue into 2003 at Cluff Lake, and continues at Key Lake in combination with treatment of ore from McArthur River. Similarly, milling of stockpiled ore will continue at McClean Lake for some 3 years, prior to receiving ore from the Cigar Lake mine, targeted for production in 2006. Industry leaders Cameco Corporation and COGEMA Resources Inc. control 57% and 35% respectively of known reserves in the Athabasca Basin, and operate all of the aforementioned mines.

Total Saskatchewan reserves in the lower cost categories (up to $150/kg U) exceed 350 000 t U, which rep-

Table 10 – Uranium reserves and resources in Saskatchewan, 2001.

Ownership (operator first)	Share (%)	Property or deposit	Reserves (unstandardized)				Production				Comments
							2000		2001		
			t U	lb. U_3O_8 (x 10^6)	% U	% U_3O_8	t U	lb. U_3O_8 (x 10^6)	t U	lb. U_3O_8 (x 10^6)	
Reserves:											
Cameco Corporation	100.0	Eagle Point	8 603	22.4	1.1	1.3	2 790	7.3	1 755	4.6	On care-and-maintenance since June 2001; 2001 production from stockpile; re-opened in 2002
Cameco Corporation COGEMA Resources Inc.	83.333 16.667	Key Lake	460	1.2	0 35	0.41	4 141	10.8	6 924	18	McArthur River ore blended with stockpiled Key Lake ore; largest uranium milling complex in world; mill retrofit cost $21M
Cameco Corporation COGEMA Resources Inc	69.805 30.195	McArthur River P2N	151 742	394.5	18	21.18					Largest uranium mine in world; start-up Nov. 2000; 11 million lb. U_3O_8 in first year; projected 18 million lb./year; max. 25 year life
Cigar Lake Mining Corp: Cameco Corporation COGEMA Resources Inc. Idemitsu Uranium Exploration Canada Ltd. TEPCO Resources Inc.	 50.025 37.100 7.875 5.000	Cigar Lake	89 076	231.6	15.4	18.21 *19.77*	Nil	Nil	Nil	Nil	Second largest uranium mine in world; mine start-up not before 2005; will use jet-boring non-entry within frozen ore body; $350 million development cost
COGEMA Resources Inc.	100.0	Cluff Lake	1 654	4.3	2.2	2.6	1 462	3.8	1 231	3.2	Mining ended in May 2002; milling ended December 2002
COGEMA Resources Inc. Denison Mines Ltd. OURD (Canada) Co. Ltd	70.0 22.5 7.5	McClean Lake: Sue A, B, C, and D McClean Jeb	 10 117 5 077 400	 26.3 13.2 1.0	 1.36 1.79 0 45	 1.6 2.1 0.53	2 308	6.0	2 308	6.0	Mine and mill cost $500 million; Sue C1, C2 extension, Jeb mined out; stockpiled ore to last to 2005; mining suspended in 2002
COGEMA Resources Inc. Redstone Resources Inc Tenwest Uranium Ltd. OURD (Canada) Co. Ltd.	54.8 20.7 20.0 4.5	Midwest deposit at McMahon Lake	13 755	35.7	3.8	4.5	Nil	Nil	Nil	Nil	No date set for start-up; will use jet-boring non-entry within frozen orebody as at Cigar Lake to produce 2200 t U/yr. for 6 yrs.
Resources:											
Cameco Corporation COGEMA Resources Inc. JCU (Canada) Expln. Co. KEPCO	58.000 20.115 19.000 2.885	Dawn Lake	4 977	12.9	1.43	1.69					
Cameco Corporation COGEMA Resources Inc.	69.805 30.195	McArthur River P2N	55 924	145.4	9.11	10.74					
Cigar Lake Mining Corp: Cameco Corporation COGEMA Resources Inc. Idemitsu Uranium Exploration Canada Ltd. TEPCO Resources Inc.	 50.025 37.100 7.875 5.000	Cigar Lake	45 620	118.6	14.4	16.92					

Figure 58 – Large-scale mining at the Sue pit, McClean Lake operation.

resent approximately 75% of Canadian reserves. The majority of these reserves are contained within two major deposits, Cigar Lake and McArthur River (P2 North). Total current reserves and resources exceed 4 000 000 t U_3O_8, and will last for more than 25 years at current mining rates (Table 10). This amount does not include reserves from potential new mines associated with the recent discoveries at Moore Lake, Caribou Lake and the Millennium zone.

Aggregate

Sand and gravel deposits are, for the most part, intimately related to the history of glaciation, deglaciation and postglacial geomorphic processes throughout Saskatchewan. Proglacial deposits, including outwash-plain, deltaic, valley-train and meltwater-stream, and postglacial alluvial-terrace and channel deposits tend to be very large and infrequently very coarse (Mollard and Mollard, 1987). Smaller deposits are associated with kames, kame deltas, kame terraces, eskers and crevasse fillings. Ice-contact deposits are usually small, more abundant and more variable and complex. Of local significance, specifically in south-central and southwestern Saskatchewan, are the coarse Tertiary quartzite gravels of the Eocene-Oligocene Cypress Hills Formation and the Miocene Wood Mountain Formation. These gravels, and their reworked equivalents, provide material for direct use or as crushed rock.

Mollard and Mollard (1987) indicated, on the basis of about 10 000 gravel prospects mapped from airphotos in the past 40 years, that there is about one small sand and gravel prospect for every 26 km^2 and about one large prospect for every 2600 km^2 investigated. Most of the larger deposits range from 2.5 million to 12.7 million t. The largest contains about 1 billion t.

The relative abundance, ease of discovery and widespread occurrence of sand and gravel deposits throughout much of Saskatchewan have resulted in a paucity of published information on the resource. The earliest are probably those of the Geological Survey of Canada from 1916 to 1920. Some of the most significant publications, with respect to sand and gravel resource location, are those of the Saskatchewan Research Council, particularly by E.A. Christiansen between 1956 and 1970 on glacial and surficial geology, groundwater, preglacial valleys and Pleistocene stratigraphy. Geotechnical engineering and geological consulting firms, rural municipalities, private contractors and the provincial highway construction authorities have made considerable contributions to sand and gravel resource location, development and supply. Few of these data, however, are available for publication. The depletion of many of the small deposits, particularly in proximity to some urban areas, is a concern of growing significance. The rising cost of transportation from more distant deposits has aggravated this problem for many communities. The Saskatchewan Research Council has produced a series of aggregate-resource maps, including 1:250 000-scale surficial-geology and aggregate-resource potential maps, and 1:50 000-scale aggregate-resource maps for areas around urban centres.

Base Metals (Copper-Zinc-Lead)

History

Like the serendipity of the initial pitchblende discovery in the Beaverlodge district during the gold rush in the early 1930s around Goldfields, it was the discovery of a small copper-zinc showing in 1915 by Thomas Creighton and the Mosher and Dion brothers, during the gold rush around Amisk Lake, that gave rise to the development of the truly world class, Flin Flon Paleoproterozoic VMS district. This discovery resulted in a change in emphasis to base-metal prospecting and, that same summer, the Mandy high-grade copper deposit was found on Schist Lake, a short distance to the south in Manitoba. The Mandy produced initially from 1917 to 1920, although only the highest grade copper ore could be mined economically because of the cost of hauling the ore by horse-drawn sleigh, barge and train to the Trail smelter in southern British Columbia. The Flin Flon deposit would wait until 1931 for the first production by the Hudson Bay Mining and Smelting Co. Ltd. (HBMS), because the ore was not of sufficiently high grade to ship without concentration of the copper and zinc sulphides. The metallurgical problems of separating these economic minerals from the dominant pyrite would not be solved until 1927. Power for the operation was, and continues to be, provided by a hydroelectric plant constructed at Island Falls on the Churchill River, some 100 km to the north. The main orebody was exhausted in 1992 after 60 years of production.

After World War II, some base-metal prospects found before the war were reactivated and new discoveries were made. Among the former was the Anglo-Rouyn mine, at the site of the copper prospect noted by McInnes and later staked by the Hall brothers in 1915. The mine produced essentially copper, but the ore was significantly endowed with gold and silver. It operated between 1966 and 1972. Concentrate was shipped via the Hanson Lake road to the Flin Flon smelter. The Rottenstone deposit was also mined at this time (1965-1968). It was a small but successful producer of nickel, copper, platinum and palladium, together with some silver and gold. Operation was seasonal, with mining and milling in the summer and shipping in the winter. Concentrate was shipped to Sudbury for refining.

Several ore deposits were found in the immediate Flin Flon area and developed as essentially copper-producing satellite mines to the main Flin Flon mine of HBMS. Of these, the Birch Lake mine was discovered by Flin Flon prospector Joe Brain in 1949, and the deposit was mined by HBMS between 1957 and 1960. The Flexar and Coronation mines were discovered by Hudson Bay Exploration and Development Co. Ltd. (HBED) in 1951 and 1953, respectively. The former produced between 1969 and 1972, and the latter between 1960 and 1965. This success followed from the saturation geophysics approach to exploration pioneered for HBMS by Albert Koffman. This exploration technique was responsible for many of the company's successes in Manitoba.

In 1957, the Parrex Mining Syndicate discovered a small-tonnage, high-grade, lead-zinc-silver deposit beneath Hanson Lake, some 65 km west of Flin Flon. This subsequently became, in 1967, the Western Nuclear mine; however, the orebody did not meet expectations and the mine closed in 1969 due to exhaustion of the ore.

Other areas of the Shield, aside from that surrounding Flin Flon, were showing some potential. Between 1944 and 1965, several subeconomic discoveries were made in the La Ronge Belt, at Brabant Lake (zinc-copper), Nemeiben Lake and Gochager Lake (nickel-copper), and Borys Lake (zinc-lead). In addition, a new metallogenic province was being identified in the 1950s and 1960s in the well-defined 500 km long belt of metasediments (Wollaston Belt) stretching from Sandfly Lake on the Churchill River through Wollaston Lake into northwestern Manitoba. Because much of the belt is covered by glacial drift, exploration involved prospecting for mineralized boulders and tracing them back to their source by identifying boulder trains. Prospector Eric Partridge and geologist Murray Pyke deserve special mention for their contribution to this effort.

The first base-metal mineralization in the Wollaston Belt was found in 1953 during the search for uranium in the Foster Lakes area. Simon Eninew, a prospector working for Partridge, found a large boulder of meta-arkose, with copper stain but no copper, south of Juno Lake near the Wathaman River. It assayed more than 2% Cu (present as chalcocite). Partridge and Falconbridge Nickel Mines Ltd. discovered other boulders and a frost-heaved outcrop with copper mineralization in 1962. More spectacular was the discovery of the Wathaman River boulder, a quartzite containing galena and assaying an impressive 16% Pb. It precipitated a search for quartzite-hosted lead-zinc mineralization in the area 'up ice' and, in 1966, the George Lake zinc-lead deposit, located some 65 km to the northeast, was drilled. Other discoveries of quartzite-hosted lead-zinc mineralization followed in the late 1960s at Johnston Lake and Sito Lake, among other locations. While Falconbridge was active at George Lake, Great Plains Development Ltd. commenced a prospecting program in the vicinity of the original copper discoveries and was successful in identifying several other prospects. Nevertheless, neither these nor the lead-zinc discoveries have yet proven to be economic.

Through the boom years of exploration for uranium in the 1970s and the low metal prices of the 1980s, base-metal exploration stagnated, with activity essentially restricted to the Flin Flon area and the Shield edge to the west. In 1982, Granges Exploration AB made a significant copper-zinc discovery at Bigstone Lake, 90 km west of Flin Flon. The deposit subcrops beneath 40 m of Paleozoic rocks overlying the Shield. Two years later, Granges discovered the Balsam zone, which currently has an estimated geological resource of 147 000 t grading about 1% Cu, 2% Zn, 20 to 25 g/t (0.73 oz./ton) Ag and 1 to 2 g/t (0.029 to 0.058 oz./ton) Au.

In 1985, HBED identified the economic copper-zinc Callinan zone, 3 km north and on strike with the Flin Flon orebody and straddling the Saskatchewan-Manitoba boundary. Mining of the Callinan deposit began in April 1990, but production from the Saskatchewan portion (the upper part of the Callinan North zone) did not begin until 1997.

Successes by Granges and HBED were also recorded just across the boundary in Manitoba with drilling, in 1975, of the Trout Lake copper-zinc deposit and, in 1984, of the Namew Lake nickel-copper deposit. In 1988, a Cameco–Esso Minerals Canada Ltd.–Tri Gold Industries Inc. joint venture discovered the McIlvenna Bay zinc-copper deposit. This deposit, now optioned by Foran Mining Corporation from owners Cameco Corporation and Billiton Metals Canada Ltd., subcrops beneath Paleozoic rocks 5 km south of the old Western Nuclear mine at Hanson Lake. With more than 14.5 million t of reserves, it is the most significant Saskatchewan base-metal discovery since the Flin Flon orebody was found in 1913.

In May 1994, HBED drilled a moderate-strength anomaly, found using the new airborne Spectrum EM system, and discovered the Konuto Lake deposit near Denare Beach. Similar anomalies led to the discovery of the subeconomic Grassberry and Suggi Lake base-metal zones, approximately 72 km southwest of Flin Flon. The Konuto Lake deposit is geologically similar to the former Coronation, Flexar and Birch Lake deposits. Phase I development began in August 1997 and production commenced in April 1999.

Overall throughout the past decade, exploration for base metals has constituted at most 25% of total annual exploration expenditures for the province, and only 6% in 2002 (Figure 41).

General Geology

The distribution of base-metal deposits in Saskatchewan reflects a difference in crustal character between the northwestern and southeastern segments of the Precambrian Shield. The southeastern segment (Reindeer Zone), between La Ronge, Flin Flon and Lynn Lake (in Manitoba), is interpreted as an Early Proterozoic ensimatic regime between the Superior Craton in the southeast and the Rae-Hearne Province in the northwest. It comprises volcanoplutonic-arc material (e.g., La Ronge and Flin Flon metavolcanic belts), interarc and backarc basin sediments, and possibly exotic terranes represented by arc and microcontinental fragments. There is a marked contrast with the ensialic regime of the Rae-Hearne Province and the overlying, thick, Early Proterozoic shelf-type metasediments of the Wollaston Supergroup.

The ensimatic regime is host to essentially volcanogenic metal deposits representing both proximal and distal massive-sulphide mineralization. Proximal, volcanic-hosted massive-sulphide deposits of copper, copper-zinc, zinc and lead-zinc, epitomized by the Flin Flon and Western Nuclear mines, formed in an oceanic island-arc setting, whereas deposits that are copper-rich, such as the Birch Lake, Flexar and Coronation mines, are possibly representative of Cyprus-type copper mineralization formed in an oceanic backarc tectonic setting. Predominantly sediment-hosted copper, copper-zinc and zinc accumulations, such as the Anglo-Rouyn mine and the Brabant Lake and Borys Lake deposits, may be distal Besshi-type deposits. In contrast, the Wollaston Supergroup is host to essentially sedimentogenic deposits: 1) quartzite-hosted zinc-lead at George Lake and Sito Lake; and 2) arkose-hosted 'red bed'–type copper-lead-silver-gold at Janice Lake. These have not proven to be of economic grade.

Flin Flon District

Flin Flon Mine (Figure 59)

Geology: The mine area is underlain by Early Proterozoic metavolcanic rocks of the Amisk Group, which dip steeply, and face, to the east; the volcanic assemblage is inferred to have filled a large, fault-bounded depression, with numerous internal, fault-bounded sites of deposition (Figure 60). Footwall rocks to the west of the deposit comprise a thick sequence of mafic pillowed flows and fragment breccias. The immediate footwall to the deposit is a 200 to 300 m thick sequence of pillow-fragment breccia. Immediately overlying, to the east, is the 'Mine Rhyolite', which hosted the deposit. This unit, 150 to 180 m thick in the vicinity of the smelter complex, can be traced along strike for about 3 km and comprises two distinct phases: a lower, quartz- and plagioclase-phyric flow breccia and an upper, massive, flow-banded, quartz- and plagioclase-phyric rhyolite flow overlain by flow breccia that commonly contains slabs of flow-banded rhyolite (Figure 59); this breccia is locally referred to as 'mill rock' because of its association with sulphide deposits.

The Mine Rhyolite (and related sulphide bodies) is immediately overlain by bedded volcaniclastic rocks, comprising rhyolite clast–bearing debris flows, that are in turn overlain by a thick, relatively uniform succession of porphyritic, pillowed mafic flows. Subvolcanic sills and dikes of metadiorite intrude the metavolcanics,

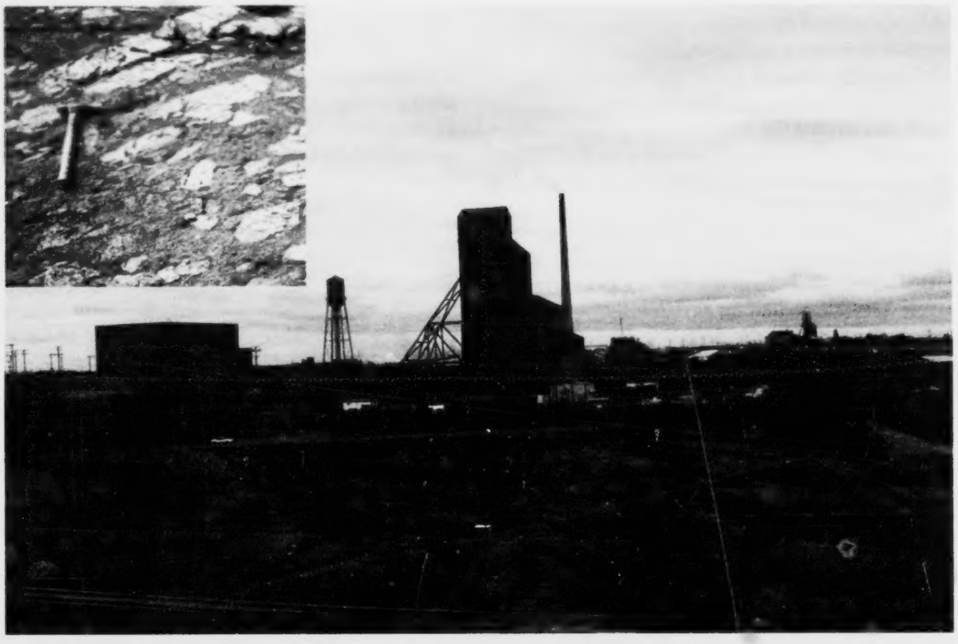


Figure 59 – Smelter stack and South Main (foreground) and Callinan (distant) headframes at the historic Flin Flon VMS mining camp, located on the Saskatchewan-Manitoba boundary. Inset shows rhyolite breccia, the so-called 'mill rock', which hosts the Flin Flon and Callinan deposits (cf. Figure 60).

as do younger, postvolcanic gabbroic bodies (the Boundary Intrusions).

These rocks outcrop in a major anticline that has subsidiary folds on its limbs. The orebodies occurred on the eastern limbs and crests of these subsidiary folds and plunged 35°SE, parallel to the fold axes. Six orebodies were identified within a zone about 800 m long by 150 m wide, and extending from surface to 1140 m in depth. The zone dips 70°E and plunges 35°SE for a distance of about 2000 m. The orebodies averaged 270 m in length, 21 m in width, 450 m in depth and 840 m in plunge length. An extensive zone of footwall alteration, comprising chlorite and chlorite-talc schists, is associated with the deposit.

Approximately 70% of the ore was contained in massive-sulphide lenses that were commonly banded; the remainder was contained in zones of disseminated sulphide adjacent to these lenses. Predominant minerals were pyrite, pyrrhotite, sphalerite and chalcopyrite. Minor minerals included arsenopyrite, cubanite, galena, tetrahedrite-tennantite, sylvanite, tetradymite, altaite, magnetite, electrum and gold. Sphalerite, galena, tetrahedrite and electrum were enriched, relative to chalcopyrite, toward the hanging-wall portions of the massive-sulphide lenses. As well, there was a close association between zinc and gold-silver in the massive-sulphide lenses. Also, copper increased in proportion, relative to zinc, gold and silver, with increasing depth in the mine.

History and Production: The Flin Flon deposit, one of the world's largest Proterozoic VMS deposits, has produced more copper and gold than all other deposits in Saskatchewan combined. The Flin Flon copper-zinc discovery was staked by Thomas Creighton and the Mosher and Dion brothers in 1915. From 1916 to 1918, 44 diamond-drill holes, totalling 7822 m, outlined the deposit to 274 m below surface. In 1920, two shafts (the No. 1 to 64 m and the No. 2 to 93 m), were sunk 150 m apart and drilling was completed on the 30, 61 and 91 m levels.

In 1921, the Mining Corporation of Canada acquired a majority interest in the property and carried out exploration work in the vicinity of the deposit. In 1925, the Witney Group of New York optioned the property and, in 1926-1927, set up a test mill. In 1927, Witney acquired a majority interest, with the Mining Corporation of Canada retaining 15%. In the same year, the Hudson Bay Mining and Smelting Co. Ltd. (HBMS) was incorporated to develop the property. Development of the mine and construction of the mill, zinc-recovery plant and copper smelter, as well as the hydroelectric plant at Island Falls on the Churchill River and the railway line from The Pas, began in 1928. Production began in 1930.

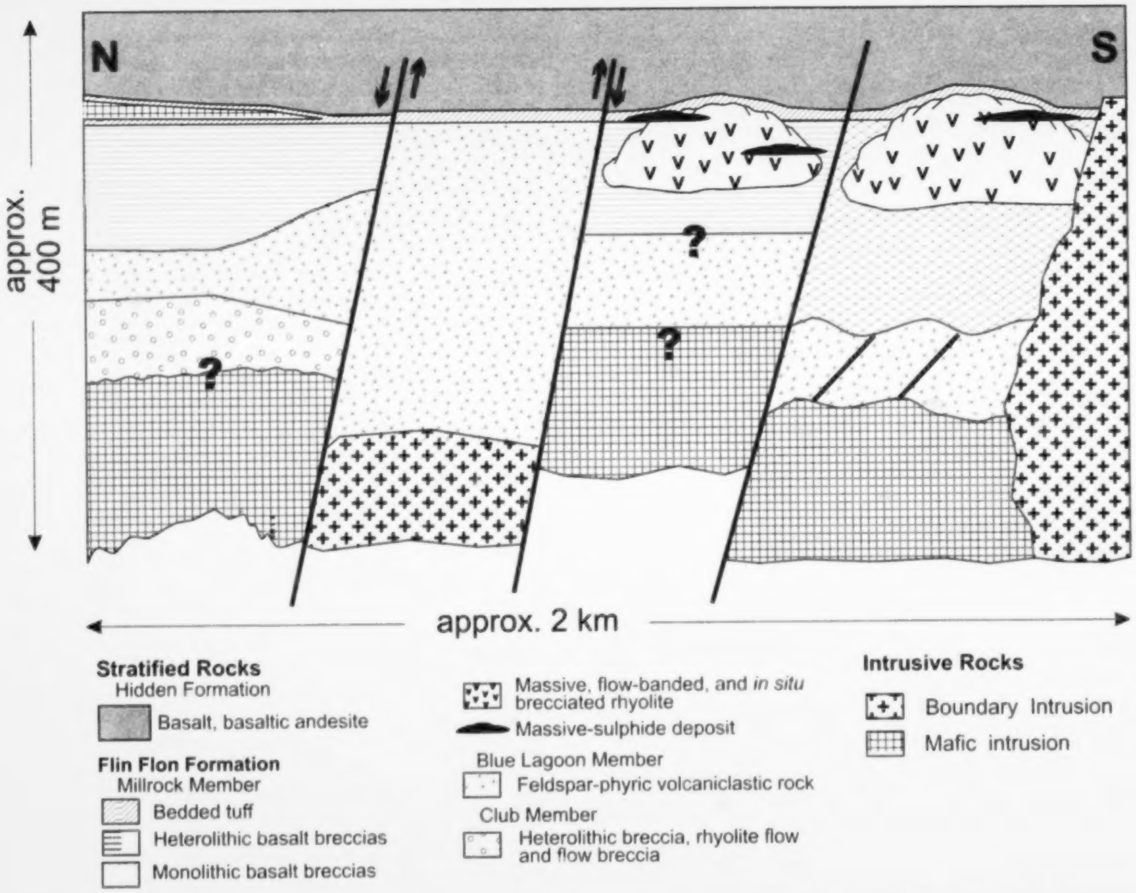

N
S
approx. 400 m
approx. 2 km
?
?
?
Stratified Rocks
Hidden Formation
Basalt, basaltic andesite
Flin Flon Formation
Millrock Member
Bedded tuff
Heterolithic basalt breccias
Monolithic basalt breccias
Massive, flow-banded, and in situ brecciated rhyolite
Massive-sulphide deposit
Blue Lagoon Member
Feldspar-phyric volcaniclastic rock
Club Member
Heterolithic breccia, rhyolite flow and flow breccia
Intrusive Rocks
Boundary Intrusion
Mafic intrusion

Figure 60 – Schematic diagram of the volcanic depressions in which the Flin Flon formation was deposited (from Devine et al., 2002). The rhyolite breccia unit which hosts the major ore deposits, is shown in Figure 59.

Mining was initially by open pit (792 m long by 137 m wide), to a depth of around 100 m. After 1937, the mining emphasis shifted to underground and has been entirely underground since 1941. Production started at 2700 t/day and reached a high of 5400 t/day during World War II. The mine has three vertical shafts: the original 676 m North Main shaft in Manitoba and, in Saskatchewan, the 1241 m South Main shaft, 1.6 km to the south, and the 991 m No. 3 shaft, 715 m south-southwest of the North Main shaft. In recent years, the South Main has been the main production shaft and it continues to be utilized for hoisting ore from the newly opened Callinan zone. Mine workings extend to the 1125 m level, and the ore zone disappears below 1140 m. A new pressure-leaching zinc plant was completed in 1993, reducing SO_2 emissions by 25% and airborne particulates by 50%.

Reserves were originally estimated at 16.3 million t grading 1.71% Cu, 3.5% Zn, 2.5 g/t (0.074 oz./ton) Au and 36.3 g/t (1.06 oz./ton) Ag. To the end of 1991, 63 million t grading 2.17% Cu, 4.13% Zn, 2.5 g/t (0.074 oz./ton) Au and 41.5 g/t (1.21 oz./ton) Ag had been extracted. Cadmium was produced as a by-product.

Callinan Deposit

Geology: The Callinan deposit is the only other ore body within the main part of the Flin Flon camp that straddles the provincial boundary with Manitoba; the Trout Lake and 777 deposits are wholly within Manitoba. The Callinan orebodies lie on the eastern limb of the Beaver Road Antiform, conformable with the stratigraphy and plunging 35 to 45°SE. Multiple massive-sulphide lenses are hosted by two quartz-phyric rhyolite units, 150 to 300 m thick, separated by a 90 m wide zone of intermediate metavolcanic rocks. The bulk of the reserves are in the Callinan South zone. The typical VMS mineralization consists of fine-grained, banded sphalerite, pyrite, pyrrhotite and chalcopyrite.

History and Production: The Callinan deposit consists of two ore bodies, the Callinan North and South. Only the upper portion of the Callinan North lies within Saskatchewan. In 1989, HBMS drove a drift from the South Main shaft of the old Flin Flon mine to the Callinan South deposit, and mining commenced in April 1990. At that time, combined proven reserves totalled 2.8 million t grading 1.43% Cu, 3.8% Zn, 1.7 g/t (0.05 oz./ton) Au and 20.6 g/t (0.6 oz./ton) Ag. Of this, the Saskatchewan portion of the Callinan North was 788 200 t grading 1.28% Cu, 3.7% Zn, 1.5 g/t (0.045 oz./ton) Au and 16.8 g/t (0.49 oz./ton) Ag.

In 1992, a diamond-drill program to define the Callinan North and extend the Callinan South and East zones improved the grade but lowered the tonnage of the Saskatchewan portion. Geological reserves calculated in 1993 for the Callinan North (Saskatchewan) were 562 200 t grading 1.71% Cu, 4.1% Zn, 2.0 g/t (0.057 oz./ton) Au and 22.64 g/t (0.66 oz./ton) Ag. Development work on the North zone continued in 1994 and 1995, and mining of the Saskatchewan portion of the zone finally started in 1997. From the start of mining in the Saskatchewan portion of the upper North zone to the end of 2000, cumulative production was 144 519 t grading 1.47% Cu, 4.17% Zn, 1.64 g/t (0.048 oz./ton) Au and 18.00 g/t (0.53 oz./ton) Ag. Mineable reserves in the Saskatchewan portion of the North zone, as of January 1, 2002, were 675 765 t of ore at an average grade of 1.19% Cu, 3.06% Zn, 1.54 g/t (0.045 oz./ton) Au and 18.32 g/t (0.534 oz./ton) Ag.

Konuto Lake Mine

Geology: The Konuto deposit is hosted by arc-type, mafic metavolcanic rocks of the Ruth Lake Assemblage, which was also host to the past-producing Coronation, Birch and Flexar deposits. The Konuto Lake deposit strikes north for more than 250 m and dips steeply east. Mineralization comprises chalcopyrite, pyrrhotite, pyrite, lesser sphalerite, and local arsenopyrite and magnetite in two steeply dipping, stacked, massive-sulphide lenses (the No.1, which contains the bulk of the mineralization, and the No. 3). Microscopically, the ore contains significant bornite intergrowths in chalcopyrite and trace amounts of cubanite, mackinawite, vallerite, tellurobismuthite, molybdenite and native gold. Hydrothermal alteration, dominated by green-black magnesium-rich chlorite, occurs between the two zones. Locally, it includes a near-ore-grade stringer zone of disseminated chalcopyrite-pyrrhotite (the No. 2 zone); this stringer zone is hosted by variably chloritized, carbonatized and silicified rocks. Mineralization extends from near surface to a depth of 550 m.

History and Production: HBMS discovered the deposit in June 1995 by drilling a moderate-strength airborne-EM anomaly. Project permits were received in 1996 and phase I of underground exploration began in August with development of a ramp to the 140 m level. The geological resource estimate on January 1, 1997 was 1.41 million t grading 5.27% Cu, 1.44% Zn, 2.1 g/t (0.061 oz./ton) Au and 10.47 g/t (0.305 oz./ton) Ag. The underground ramp reached the 240 m level, and undercutting of the No. 1 and No. 2 lenses on the 140 m level began in April. Production started in July 1997 and, by September 20, 1999, the ramp had reached the 315 m level of the No. 3 lens. Ore is trucked to the Flin Flon smelter for processing.

Cumulative production from start-up to the end of 2000 was 572 417 t grading 4.48% Cu, 1.16% Zn, 1.99 g/t (0.058 oz./ton) Au and 9.25 g/t (0.27 oz./ton) Ag. On January 1, 2001, mineable reserves and resources were 1 296 802 t grading 4.04% Cu, 1.50% Zn, 2.154 g/t (0.063 oz./ton) Au and 8.403 g/t (0.245 oz./ton) Ag. Production was suspended from March 21 to August 2, 2001 during a period of particularly bad metal prices.

Birch Lake Mine

Geology: The Birch Lake orebody occurred in sheared andesitic Amisk volcanic rocks (chlorite schists), as a series of tabular massive-sulphide ore zones with an average width of 2 m and lengths of 45 to 90 m. It consisted of mainly chalcopyrite, pyrrhotite and pyrite, with lesser amounts of magnetite and sphalerite. Contacts with surrounding meta-andesites were sharp and alteration was confined within the zone of shearing, which extended for only a short distance on either side of the orebody.

History and Production: The Birch Lake deposit, discovered by prospector Joe Brain in 1949, was optioned by HBMS that year and diamond-drilled in 1951-1952. Development work, between 1952 and 1956, consisted of drilling, the sinking of a 502 m, three-compartment shaft and lateral work on six levels. Production commenced in 1957 and continued until the ore was exhausted in 1960. Ore was trucked to the nearby Coronation mine and then hauled to Flin Flon by company railway. Total production was 278 690 t grading 6.17% Cu, 0.1 g/t (0.003 oz./ton) Au and 4.1 g/t (0.12 oz./ton) Ag. Some zinc, selenium, tellurium and cadmium were also produced.

Coronation Mine

Geology: The Coronation deposit occurred in Amisk metavolcanic rocks, comprising andesitic flow and breccia and basic tuffs, intruded by granodiorite and gabbro. Three ore shoots occupied a weakly discordant zone of shearing, which had been traced over a distance of 6.5 km. They occurred within an envelope of lower grade mineralization that was 275 m long, up to 37 m wide and more than 300 m thick. As mined, the deposit was 182 m long, up to 20 m wide and 320 m deep. The ore comprised massive pyrrhotite, pyrite and chalcopyrite, with minor sphalerite and magnetite.

History and Production: The Coronation deposit was discovered in 1953 by HBMS through diamond-drilling of an electromagnetic anomaly. In 1955 to 1956, a three-compartment shaft was sunk to a depth of 455 m and levels were established at 46 m intervals. An adjacent two-compartment shaft was sunk to 322 m in 1958, and underground drilling was carried out to establish reserves. From 1960 until depletion of the orebody in 1965, the mine produced a total of 1 281 465 t of ore grading 4.25% Cu, 0.3% Zn, 2.0 g/t (0.059 oz./ton) Au and 4.8 g/t (0.14 oz./ton) Ag. Production was greater than the initially calculated reserves due to discovery of additional ore, and through lowering of the cut-off grade during the later stages of mining.

Flexar Mine

Geology: The geological setting of the Flexar deposit is similar to that of Birch Lake. Ore occurred in chlorite schist and comprised chalcopyrite, pyrrhotite, pyrite, magnetite and sphalerite.

History and Production: The Flexar mine was located 1.5 km north of the Birch Lake mine, and appeared to lie within the same structure. HBMS acquired the property from prospector Joe Brain in 1952 and drilled the structure, outlining a small copper deposit. In 1963, a power line was extended to the property, mine development was initiated and a shaft was sunk to 356 m. The shaft was deepened to 418 m in 1968, and the mine was brought into production in 1969. The orebody was exhausted in 1972, after yielding 305 940 t of ore grading 3.75% Cu, 0.47% Zn, 1.4 g/t (0.04 oz./ton) Au and 8.9 g/t (0.19 oz./ton) Ag.

Base-Metal Deposits Outside the Flin Flon VMS District

Anglo-Rouyn Mine

Geology: The Anglo-Rouyn mine was located at the north end of Lac La Ronge, within the Glennie Domain, near the southern limit of exposed Precambrian rocks in Saskatchewan. The deposit was in northwest-dipping metasedimentary gneisses, which are structurally overlain by sheared granodiorite. The metasediments comprise quartzofeldspathic and intermixed calcareous, diopside-amphibole-epidote–bearing gneisses of uncertain origin. The three ore zones formed en échelon lenses dipping northwest and plunging gently to the southwest, parallel to a prominent tectonic lineation. Ore zones, ranging in width from 0.3 to 10 m, consisted of stringers and veins of quartz, pyrite, pyrrhotite and chalcopyrite that averaged more than 2% Cu. Magnetite, sphalerite, galena and pentlandite were present in small amounts. Mineralization has been traced along strike for about 8 km to the northeast and southwest of the deposit.

History and Production: The Moose Point copper showing on Lac La Ronge, discovered by McInnes in 1908, was staked by the Hall brothers in 1915. The Consolidated Mining and Smelting Co. of Canada Ltd. undertook the first trenching and drilling on the property in 1929; however, they dropped their option and eventually, in 1950-1951, the property lapsed. Restaking occurred in 1951-1953, and the new claims were acquired by Anglo-Rouyn Mines Ltd. Extensive exploration led to underground development in 1955 and, by the following year, a shaft had been completed to 166 m and four levels established. By the end of 1956, however, underground activity had been suspended.

Some diamond-drilling was done from surface in 1957, after which the property remained dormant until 1963, when additional claims were staked. Rio Algom Mines Ltd. carried out further exploration work and a decision was made to bring the property into production.

Construction of a mill began in 1965, and the shaft was dewatered and deepened to 244 m. The 900 t/day mill was completed in January 1966 and the first shipment of concentrate made to the Flin Flon smelter by road a month later. Reserves were estimated at 1.8 million t grading 2.4% Cu and 0.6 g/t (0.018 oz./ton) Au after dilution.

Underground mining was augmented by two open pits that yielded some 198 600 t of ore, approximately 12% of total production. Reserves were exhausted in 1972. Total production was 1 716 770 t at a calculated grade of 1.71% Cu, 1.2 g/t (0.036 oz./ton) Au and 5.5 g/t (0.16 oz./ton) Ag.

Western Nuclear Mine (Hanson Lake Mine)

Geology: The deposit was located near the southwestern shore of Hanson Lake, in the southern part of the Flin Flon Domain. It was hosted by metavolcanic rocks of Early Proterozoic age, comprising interlayered dacite, mafic tuff and quartz-sericite-fuchsite schists intruded by a sill-like quartz-feldspar porphyry. It was subvertical and north-trending, and consisted of several high-grade lenses of massive sulphides consisting mainly of sphalerite and galena with minor arsenopyrite, pyrite, pyrrhotite, chalcopyrite, argentite, tetrahedrite and gold. The deposit was about 450 m long and up to 10 m wide, and plunged 12°N.

History and Production: During 1956 and 1957, Parrex Mining Syndicate (Trust) acquired, by staking and option, more than 1200 claims near the southwestern shore of Hanson Lake. Airborne geophysics and ground follow-up outlined an anomaly that was drilled during 1957-1960, resulting in the discovery of a flat-lying orebody estimated to contain 113 375 t grading approximately 21% combined Pb+Zn. In 1965, the property was purchased by Share Mines and Oils Ltd., who carried out further drilling and increased reserves to an estimated 229 500 t grading 8.08% Pb, 11.42% Zn, 0.61% Cu, 1 g/t (0.031 oz./ton) Au and 162.5 g/t

(4.74 oz./ton) Ag. An agreement was reached with Western Nuclear Inc. for production financing and a shaft was sunk in 1966 to 205 m some 200 m west of the orebody, which lay beneath Hanson Lake.

Production began in 1967 and lasted until the orebody was mined out in 1969. The deposit produced a total of 147 301 t of ore averaging 5.83% Pb, 9.99% Zn and 0.51% Cu.

McIlvenna Bay Deposit

Geology: The McIlvenna Bay deposit is located south of Hanson Lake, beneath Phanerozoic cover, immediately southeast of the old Western Nuclear mine. The deposit consists of massive and stringer sulphide zones conformably hosted by a variably altered felsic-volcanic succession. A sequence of alternating basalt, chert, dacite and banded oxide facies iron formation lies structurally above the ore zones, and blue quartz–phyric sericite schists, sericitized rhyolite and felsic ash tuffs lie structurally below them. The Main lens (No. 2) and four subsidiary lenses (No. 3, 4, Upper West zone and Copper Stringer zone), all of them subparallel, strike 300°, dip 60 to 75°NE and plunge 35 to 40°NW (Gracie and Tourigny, 2001). Massive-sulphide mineralization consists of rounded to oval pyrite grains set in a matrix of pyrite, sphalerite, minor chalcopyrite, and local galena, marcasite and magnetite. Chalcopyrite is the dominant sulphide in the 1 to 60 m thick stringer zone. Lens 2 hosts the bulk of the reserves. It has a strike length of 650 m, is open at depth beyond 900 m, and shows constant grade and thickness.

History and Production: Between 1983 and 1988, regional airborne geophysical surveys (INPUT and magnetic), followed by ground HLEM and magnetic surveys, mapping, prospecting, rock sampling, and finally diamond drilling, were conducted over the Hanson Lake area by SMDC on behalf of their joint-venture partners, Esso Minerals Canada Ltd. and Tri Gold Industries (later Trimin Resources Inc.). The discovery of the first significant mineralization was announced in April 1988 and, by the end of the year, 27 diamond-drill holes, totalling 8600 m, had outlined a deposit with a strike length of 600 m and extending to a depth of 500 m. Further drilling and ownership changes followed between 1989 and 1990, when the deposit was owned jointly by Cameco Corporation (67.1%; operator) and Trimin Resources Inc. (32.9%). Billiton Metals Canada Inc. purchased Trimin's share for $17.5 million in 1991. Mineable reserves in 1992 were estimated at 13.82 million t grading 0.83% Cu and 4.66% Zn, but a 1993 re-evaluation of previous drill results gave revised figures of 13.1 million t grading 1.26% Cu, 4.95% Zn, 0.52 g/t (0.015 oz./ton) Au and 24.3 g/t (0.71 oz./ton) Ag. The property remained dormant from 1994 to 1998, when Foran Mining Corporation agreed to purchase the deposit from Cameco Corporation and Billiton Metals Canada Ltd. for an initial price of $3 million. An additional $7 million was to be paid within the next three years in conjunction with completion of a feasibility study. Foran re-assessed previous work and released a revised resource estimate of 27.2 million t grading 0.90% Cu, 3.27% Zn, 0.34 g/t (0.01 oz./ton) Au and 16.5 g/t (0.48 oz./ton) Ag.

Evaluation continued in 1999 with a 5500 m phase I infill-drilling program that raised a portion of the No. 2 lens to the probable category. Phase II stepout diamond-drilling, totalling 9500 m, was completed to expand the known geological resource. The copper-gold stringer zone was expanded, the smaller zones were better defined, and the potential size of the deposit was increased. On November 4, 1999, an independent, audited, revised resource estimate was released. Total combined indicated and inferred resources from the No. 2 lens massive sulphide and the newly discovered Upper West zone were quoted as 11.4 million t grading 0.94% Cu, 6.08% Zn, 0.45% Pb, 0.45 g/t (0.01 oz./ton) Au and 24.40 g/t (0.71 oz./ton) Ag. Total indicated and inferred resources in the copper stringer zone were given as 11.7 million t grading 1.79% Cu, 0.48% Zn, 0.57 g/t (0.017 oz./ton) Au and 11.96 g/t (0.35 oz./ton) Ag.

Continued diamond-drilling in 2000 led to the release of an audited, revised resource estimate on July 5. Combined indicated and inferred resources for the No. 2 lens massive sulphide, Upper West zone and No. 3 lens massive sulphide were now given as 14.5 million t grading 0.91% Cu, 6.08% Zn, 0.40% Pb, 0.45 g/t (0.013 oz./ton) Au and 23.70 g/t (0.69 oz./ton) Ag. Combined indicated and inferred resources for the Copper Stringer zone and No. 4 lens were given as 12.1 million t grading 1.81% Cu, 0.54% Zn, 0.63 g/t (0.018 oz./ton) Au and 12.47 g/t (0.367 oz./ton) Ag.

Resources and Current Production

Base-metal production in the province has been dominated for the past century by Hudson Bay Mining and Smelting Co. Ltd. with its copper-zinc mining and smelting operations at Flin Flon, located on the Saskatchewan-Manitoba boundary (Table 11). From 1930 to the end of 1991, a total of 62.5 million t of ore have been extracted from the world-class Flin Flon orebody, of which 43.2 million t have been from Saskatchewan. In 1989, production effectively ceased with depletion of the orebody, and the mine and few remaining ore reserves were utilized for training miners. Gold, silver, tellurium, selenium and cadmium were by-product metals recovered with the copper and zinc. Between 1957 and 1972, several smaller mines operated for short periods of time. Of these, the Birch, Coronation and Flexar were primarily copper producers developed by HBMS as satellites to the main Flin Flon orebody, although the Coronation ore had significant zinc, silver and gold. The Anglo-Rouyn mine of Rio Algom Mines Ltd., at Moose Point on Lac La Ronge, yielded copper

Table 11 – Historical base-metal production in Saskatchewan, including by-products.

Map no.[1]	Mine	Years mined	Production (t)	Metal produced (kg)									
				Cu	Zn	Pb	Ni	Au	Ag	Pt	Pd	Se+Te	Cd
Cu-Zn 24	Flin Flon (total)	1930–91	62 521 676			not available							
Cu-Zn 24	Flin Flon (Sask.)	1930–91	43 179 458[2]			not available							
Cu-Zn 25	Birch Lake	1957–60	278 750	15 309 383	18 398	-	-	25	957	-	-	19 611	34
Cu-Zn 27	Coronation	1960–64	1 281 750	48 959 997	2 249 945	-	-	2 335	5 208	-	-	53 543	5 653
Cu-Ni 6	Rottenstone	1965–68	26 058	-	-	-	654 116	11	91	63	112	-	-
Cu-Zn 10	Anglo-Rouyn	1966–72	1 717 150	28 777 038	-	-	-	2 104	9 586	-	-	-	-
Pb-Zn 6	Western Nuclear	1967–69	147 350	528 461	9 636 955	5 537 852	-	31	11 785	-	-	-	-
Cu-Zn 25	Flexar	1969–72	306 000	11 447 391	-	-	-	229	-	-	-	-	-

[1] number refers to Mineral Resource Map of Saskatchewan, back pocket

[2] average grade of ore for the Flin Flon mine (Saskatchewan portion) reported as 2.21% Cu, 4.17% Zn, 2.5 g/t (0.073 oz./ton) Au, 42.2 g/t (1.22 oz./ton) Ag

and by-product gold and silver between 1966 and 1972. Western Nuclear Inc. produced zinc, lead, copper and some silver from the Hanson Lake mine, located 65 km west of Flin Flon, between 1967 and 1969.

The only base-metal production in 2002 was from the Konuto Lake and Callinan mines, in the historic Flin Flon mining camp. Both mines are owned and operated by Hudson Bay Mining and Smelting Co. Ltd., a subsidiary of Anglo American Ltd. Commercial production at Konuto, located south and west of the main camp, began in 1999 and, as of January 1, 2002, reserves and resources were 1.18 million t grading 3.93% Cu, 1.54% Zn, 2.11 g/t (0.062 oz./ton) Au and 8.36 g/t (0.244 oz./ton) Ag, with a production rate of around 300 000 t/year. Callinan is in the heart of the Flin Flon mining camp. There are three separate, east-plunging sulphide bodies hosted within rhyolite that is correlated with the 'Mine Rhyolite' at the Flin Flon mine. Part of the Callinan North deposit is within Saskatchewan, for which production during the first 8 months of 2002 was 61 225 t of ore at an average grade of 1.57% Cu, 2.46% Zn, 1.51 g/t (0.044 oz./ton) Au and 10.9 g/t (0.318 oz./ton) Ag. Mineable reserves in the Saskatchewan portion of the North zone, as of January 1, 2002, were 675 765 t of ore averaging 1.19% Cu, 3.06% Zn, 1.54 g/t (0.045 oz./ton) Au and 18.32 g/t (0.534 oz./ton) Ag. Reserves and resources for various base-metal deposits and exploration prospects are summarized in Table 12.

Table 12 – Base-metal reserves for selected mineral deposits and exploration properties in Saskatchewan.

Map no.[1]	Deposit	Production (t)	Cu (%)	Zn (%)	Pb (%)	Ni (%)	Au g/t (oz./ton)	Ag g/t (oz./ton)
Cu-Zn 17	McIlvenna Bay	14 500 000	0.91	6.08	0.40	-	0.45 (0.013)	23.70 (0.69)
Cu-Zn 24	Callinan North[2]	562 000	1.7	4.1	-	-	2.0 (0.006)	22.6 (0.66)
Cu-Zn 26	Konuto Lake[3]	1 410 000	5.27	1.44	-	-	2.1 (0.06)	10.47 (0.31)
Cu-Zn 22	Otonodah	120 000	2.8	1.2	-	-	0.55 (0.16)	7.9 (0.23)
Cu-Zn 20	Fon	5 126 000	-	4.6	-	-	-	-
Cu-Zn 21	Schotts	1 982 750	2.61	1.35	-	-	-	-
Cu-Zn 19	Keputch	739 000	2.15	1.77	-	-	0.1 (0.003)	7.9 (0.23)
Cu-Zn 15	Bigstone	1 451 000	2.9	-	-	-	-	-
		308 000	-	11.2	-	-	-	-
Cu-Zn 7	Brabant	3 500 000	0.54	4.5	0.24	-	0.2 (0.006)	17.2 (0.50)
Pb-Zn 2	George	4 535 000	-	2.65	0.35	-	-	-
	(Brakewell)	(incl. 2 630 000	-	3.67	0.53)			
Cu-Ni 9	Nemeiben	1 450 000	0.42	-	-	0.81	-	-
Cu-Ni 7	Gochager	4 660 000	0.08	-	-	0.31	-	-
Cu-Ni 4	Axis	1 360 000	0.04	-	-	0.94	0.34 (0.01)	3.4 (0.1)
Cu-Ni 2	Dinty	1 360 000	-	-	-	0.6	-	-

[1] number refers to Mineral Resource Map of Saskatchewan, back pocket

[2] producing since 1997

[3] producing since 1998

Base Metals (Nickel-Copper)

At about the time the Flin Flon deposit was discovered in 1915, exploration for nickel was initiated in the eastern part of Lake Athabasca by H.V. Dardier, sponsored by the British armaments firm of Vickers. The exploration was stimulated by Tyrrell's report of noritic rocks, which were recognized, by analogy with Sudbury, to be a potential host to nickel mineralization. Two Davis-Calyx steam-powered shot drills were initially used for sampling. Parts from these drills are now preserved in the Western Development Museum in Saskatoon. The expedition, in reality, was a failure, although the subsequent discovery in 1928 by Dominion Explorers of a small, low-grade copper-nickel deposit at nearby Axis Lake suggests that it was justified.

Major, economic, magmatogenic nickel-copper deposits are unknown in Saskatchewan, although, just beyond the Manitoba boundary, the significant Lynn Lake deposits occur in the strike extension of the La Ronge metavolcanic belt, and the Namew Lake deposit occurs in the Flin Flon belt. In Saskatchewan, only the small Rottenstone deposit has proved economic, largely due to its extraordinarily high precious-metal content. Subeconomic reserves have been identified in mafic and ultramafic bodies of various origins in both Archean and Early Proterozoic rocks, such as those at Nemeiben and Gochager lakes northeast of La Ronge, and at Axis and Dinty lakes north of Lake Athabasca (Table 12).

Rottenstone Mine

Geology: The former Rottenstone mine is located in the Rottenstone Domain, some 145 km north of La Ronge. The pyroxenite-harzburgite body that hosted the Hall deposit was confined within migmatitic gneiss, itself incorporated within a granitoid biotite tonalite–trondhjemite terrain. A second showing, the 'Tremblay-Olson', located 2.5 km to the southwest, is apparently geologically similar. The Hall deposit outcropped in a rusty dome of oxidized rocks that was 46 m in diameter and rose 9 m above Rottenstone Lake. Ore was confined to a moderately to gently east-dipping sill-like harzburgite-orthopyroxenite body, approximately 55 m thick. Disseminated and net-textured sulphides constituted 20 to 50% by volume. Sulphide mineralization consisted mainly of pyrrhotite, pentlandite (or violarite) and chalcopyrite, with minor amounts of cubanite, magnetite, chromite, pyrite and sperrylite. Graphite was disseminated in the gangue and sulphides. The ore was locally chalcopyrite rich.

History and Production: Rottenstone is Saskatchewan's only mine that produced primarily nickel. The mine was operated seasonally by Rottenstone Mining Ltd. between 1965 and 1968. In addition to nickel, the mine yielded copper, platinum, palladium, gold and silver as by-product metals. Production from the mine is summarized in Table 11.

The 'hill of rotten stone', for which the deposit is named, is close to the shore of Rottenstone Lake. The hill was likely drawn to the attention of trappers Tremblay and Olson by local aboriginal peoples. The showing was staked in 1928 and acquired by the Hall brothers, who optioned it to the Consolidated Mining and Smelting Co. of Canada Ltd. This company completed 19 diamond-drill holes, but allowed the option to lapse. Three different companies carried out drilling programs between 1948 and 1962. The additional information, coupled with the rise in metal prices and the construction of a winter road north from La Ronge, provided the basis for a viable mining operation during the nonwinter months of 1965 to 1968 by Rottenstone Mining Ltd. Published reserves were estimated at 45 000 to 55 000 t of 2% Ni, 2% Cu, 7.5 g/t (0.22 oz./ton) Pt and 5.1 g/t (0.15 oz./ton) Pd. About 26 050 t of ore were extracted from the open pit to yield 5047 t of concentrate, grading 10.36% Ni, 5.74% Cu, 3.4 g/t (0.10 oz./ton) Au, 18.2 g/t (0.53 oz./ton) Ag, 11.3 g/t (0.33 oz./ton) Pt and 18.2 g/t (0.53 oz./ton) Pd. All that remains of the deposit is the flooded pit.

Brines

Deep formation brines are the source of a wide variety of industrial minerals, including compounds of bromine, iodine, lithium, magnesium, boron and potassium (Table 13). In some cases, the brines support free-standing mineral recovery; in other cases, the brines are coproduced with petroleum and recovery of industrial minerals from the brine is a value-added component of an integrated operation.

Virtually all Saskatchewan oil and gas is coproduced with brine. Recently published results from oilfield brine samples confirm that several elements are enriched in Saskatchewan brines. In some cases, the concentrations recorded for Saskatchewan brines approach or equal those of producing minerals-from-brine operations (Table 13). Coproduction of brine and extraction of 'economic minerals' may present an opportunity for Saskatchewan petroleum operators to turn the operating expense of brine disposal into an industrial-minerals and chemical-production revenue stream.

Building Stone

Saskatchewan has good potential for economic resources of building stone in the Precambrian Shield and along the northern fringe of the sedimentary basin, particularly in the Creighton (Flin Flon)–Deschambault Lake and La Ronge areas (Figure 61). Outcrops and subcrops of the Ordovician Red River Formation dolomites in the former area occur in an east-trending zone, about 125 km long and 10 to 30 km wide, extending from the Manitoba border to the west shore of Deschambault Lake. Dolomites in the vicinity of Limestone and Deschambault lakes are best known through studies conducted by Kupsch (1952) and under the Canada-Saskatchewan Mineral Development Agreement (MDA) in 1984. They rest on the quartzose sands of the Winnipeg Formation and, in outcrop, attain a maximum thickness of 11 m. Colours vary from silvery grey to buff, yellow, purple, red and various mottled combinations of these. They are mostly monomineralic and are classed as type III, dense, medium crystalline dolomites. Engineering tests conducted on the dolomites are summarized in Table 14.

From the test results, the quality of the dolomite in the Deschambault-Limestone lakes area appears to be adequate for application as rubble stone in a random setting or as dry pack. The dolomites have exceptionally low absorption values and have compressive strengths equal to or better than industry standards. Dolomite quarrying was undertaken in the Deschambault Lake area in 1989, by Graham Construction and Engineering (1985) Ltd., who extracted 1100 t for construction of the Agricultural Building at the University of Saskatchewan in Saskatoon. Graham has quarried smaller quantities for various projects since 1989 as demand warrants.

Table 13 – Comparison of selected Saskatchewan brines (from Rostron et al., 2002) with typical 'commercial' brines from published sources. In general, sources reported concentrations for one or a few ions, in some cases as an average value and in others as a range. The previously published values in this table should not be construed as analytical results, in that concentrations reported for any particular brine may be compiled from several different sources. Concentrations that were reported by more than one source did not always agree but were generally close, so an average of those reported values is given. The compiled data are not complete, so meaningful charge balances cannot be calculated and the sum of the separate analytes reported will not equal the reported TDS. All concentrations are expressed as mg/l. Published analyses were, in some cases, originally expressed as percent oxides or chlorides and recalculated.

Description and location	Source of	Concentration (ppm)									
		Br	Li	I	Mg	B	Ca	Cl	Na	K	TDS[1]
Published analyses of economic brines											
Brines beneath salars and playas:											
Salar de Atacama, Chile	Li, NaCl, KCl, B		1000		8000	500	500	185000	95000	20000	370000
Salar de Hombra Muerto, Argentina	Li		914		268	400	1000	195000	122000	9340	341000
Searles Lake, California	B, Li, KCl, Na_2SO_4	85	100			3000					
Dead Sea (Deep Member), Israel	Br, Mg, K	5000	25		42000		17200	219000	40000	7600	315000
Clayton Valley, Nevada	Li		200-300								
Deep formation brines:											
Smackover Formation, Arkansas	Br	3000-5000	174	26	3465	134	34000	170000	67000	2800	
Detroit River Group, Michigan	Br, I, KCl, NaCl, $CaCl_2$	1300-2500		40	10000		70000	210000	22500		313000
Morrow Formation, Oklahoma	I			300							
Tomigusku Formation, Japan	I			85							
Kasazu Group, Japan	I			100							
Seawater	NaCl, I	65	0.18	0.06	1350	4.6	400	1900	10500	380	35000
Brine inflow, Cory Mine (*from* Buchinski, 1988)	$CaCl_2$	4890			23400		138000	321000			

Saskatchewan formation brines

Sample no.	Location	Field	Formation	Br	Li	I	Mg	B	Ca	Cl	Na	K	TDS[1]
U of A 01 - 054	1-24-20-33-W1	K1 mine inflow	Prairie Evaporite	1540	31	nd	86800	3.4	1040	283500	12900	14900	401868
U of A 01 - 208 A & B	91-6-20-5-2-W2	Willmar	Frobisher	357.5	50.3	46.7	1330	240	5070	154198	89496	3610	255017
U of A 01 - 020	191-15-34-5-5-W2	Steelman	Birdbear	628.4	34	36.8	1890	204	15000	186370	92472	3890	301743
U of A 01 - 004B	21-10-3-8-5-W2	Clarilaw	Duperow	709.0	83.7	19.5	2400	195	17600	189000	91300	4710	307180
U of A 98 - 077A	11-14-6-6-6-W2	Minard	Yeoman	509.0	69.9	7.9	1620	110	13400	183000	101000	7270	308201
U of A 98 - 095A	41-8-14-4-7-W2	Kingsford	Birdbear	722.0	47.4	34.4	2190	242	18000	180011	88493	6800	297943
U of A 01 - 159 A & B	31-8-14-4-7-W2	Kingsford	Red River Group	499.0	68.6	8.1	2040	103	17500	181000	93300	4230	299523
U of A 98 - 099 A	1-4-19-4-8-W2	Macoun	Duperow	800.0	108	20.1	2170	203	18500	187766	89090	6670	306831
U of A 00 - 064 A	31-7-4-11-9-W2	Gooseberry Lake	Herald	322.0	112	3.8	2020	74	16900	187215	94600	3430	305475
U of A 98 - 123 C	31-8-18-7-11-W2	Midale	Duperow	1027.8	55.1	21.8	3570	191	28200	201807	84690	5540	326680
U of A 98 - 120 A	1-14-36-8-13-W2	Hume North	Souris Valley	934	67.4	24	3410	168	25600	199195	86885	5690	323358
U of A 00 - 025	133-3-6-5-21-W2	Hardy South	Winnipeg	20.00	2.68	0.436	127	3.53	294	37500	14500	18100	71691
U of A 00 - 033 A	1-15-2-6-21-W2	Hardy	Yeoman	42.0	4.64	81.1	7060	11.5	25300	104000	24000	1120	163051
U of A 01 - 052	13-7-36-6-W3	Cory mine inflow	Prairie Evaporite	5460	2.7	9.5	20400	108	135000	301000	8160	17200	491933

[1] total dissolved solids

In the Amisk Lake–McNally Lake area, the Ordovician dolomites appear to be less fractured and are capable of yielding substantially larger blocks. The dolomites are very hard, dense and competent, and take a very good polish. They are classified as a dolomite marble in the stone industry. Colours range from deep red to mottled red and buff to soft mottled grey and grey with buff. Aesthetically, these dolomites could gain prominence in North American markets.

Preliminary resource evaluations conducted or sponsored by the Saskatchewan Geological Survey (SGS) have revealed several promising deposits on the Precambrian Shield in the La Ronge, Pelican Narrows and Creighton–Denare Beach areas (Figure 61; Guliov, 1989; Pearse, 1990, 1991; Pearse and Guliov, 1996). Various stone types and their associated engineering characteristics are listed in Table 15. These were all surface samples, so their compressive strengths are probably lower than they would be from a quarry operation. In general, the compressive strength results are high and the absorption values are low, two valued characteristics in the building stone industry.

Some of the stones identified in the SGS resource evaluation have attracted the interest of local and, to some extent, international architectural and stone-quarrying industries, and could form the basis for development in the near-future (Table 15). Eagle Stone Ltd. was established in 1993 by a group of Saskatchewan entrepreneurs to develop certain of the most promising stone deposits in the east-central parts of the province. The company extracted several blocks of attractive green granite from a test quarry between the communities of Jan Lake and Pelican Narrows. Microfractures were evident in some of the blocks, but the material was used for polished panels in a feature wall in the North Battleford courthouse. The location selected for the test quarry is near the fault-bounded southern margin of the Sahli Granite. The fractures may not be present farther from the faulted margin in the more central parts of the granite body.

Clay

A wide variety of clays of potentially great economic significance is hosted by Cretaceous, Tertiary and Quaternary strata in southern Saskatchewan. Products currently produced include swelling bentonite, kaolinitic clays for brick making and pottery, and bloating lacustrine clay that is campaign-mined (i.e., as demand warrants) for use as lightweight aggregate. Clay and mudstone of the Tertiary Ravenscrag Formation adjacent to spontaneously combusted coal beds have been fired to the point of fusion. Locally termed 'clinker', this richly coloured material is quarried for use as a decorative aggregate in the landscaping market.

The economic and industrial significance of Saskatchewan clay resources was recognized as early as the work of Dawson (1875) and McConnell (1885). The first major studies, however, were conducted by Ries and Keele (1913), Rose (1916) and Davis (1918). Among many other clay-related investigations in the province, the work of McLearn (1928, 1930) and Worcester (1950) are outstanding. Although Worcester had published numerous clay-related papers, he synthesized 20 years of investigations from 1927 to 1947 in his 1950 report, which remains an exceptional reference.

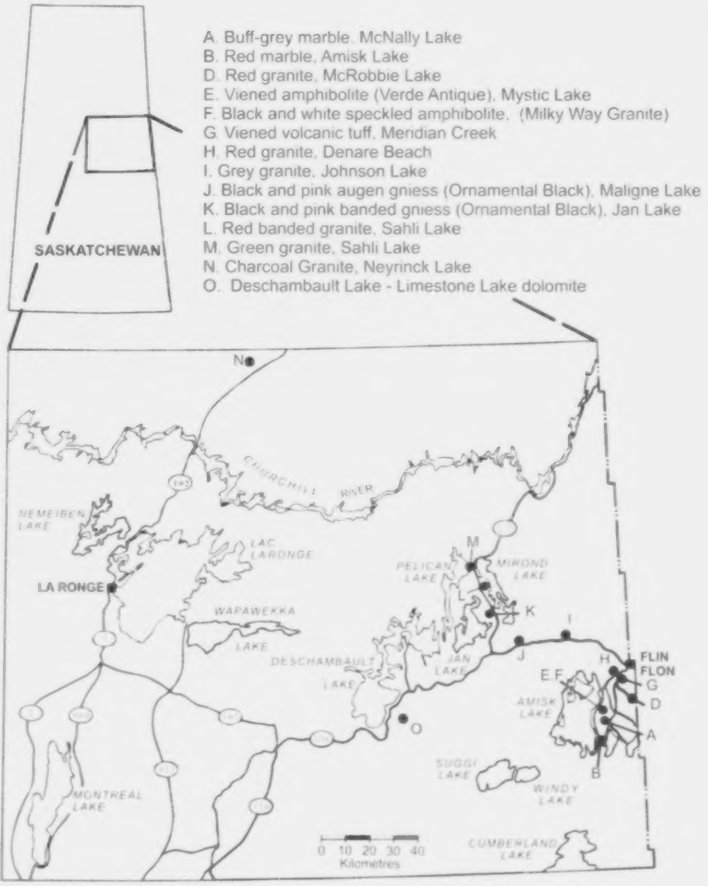

A. Buff-grey marble, McNally Lake
B. Red marble, Amisk Lake
D. Red granite, McRobbie Lake
E. Viened amphibolite (Verde Antique), Mystic Lake
F. Black and white speckled amphibolite, (Milky Way Granite)
G. Viened volcanic tuff, Meridian Creek
H. Red granite, Denare Beach
I. Grey granite, Johnson Lake
J. Black and pink augen gniess (Ornamental Black), Maligne Lake
K. Black and pink banded gniess (Ornamental Black), Jan Lake
L. Red banded granite, Sahli Lake
M. Green granite, Sahli Lake
N. Charcoal Granite, Neyrinck Lake
O. Deschambault Lake - Limestone Lake dolomite
SASKATCHEWAN
N
CHURCHILL RIVER
NEMEIBEN LAKE
LAC LARONGE
LA RONGE
WAPAWEKKA LAKE
PELICAN LAKE
M
MIROND LAKE
K
I
JAN LAKE
J
DESCHAMBAULT LAKE
O
H
FLIN FLON
E F
G
D
AMISK LAKE
A
B
SUGGI LAKE
WINDY LAKE
MONTREAL LAKE
CUMBERLAND LAKE
0 10 20 30 40
Kilometres

Figure 61 – Location of principal building stone sources in Saskatchewan (from Pearse and Guliov, 1996).

Table 14 – Engineering tests of 10 colour varieties of dolomite (from Mysyk and Edwards, 1985).

Parameter	Range
Average water absorption	0.35–0.90%
Average bulk specific gravity	2.498–2.872
Average compressive strength	(dry) 143–203 MPa[1] (wet) 68–163 Mpa
Modulus of rupture (3 samples)	(dry) 17.5–23.1 Mpa (wet) 11.6–15.8 Mpa
Magnesium sulphate soundness (% loss; 4 samples)	0.1–1.8%
Chemical analyses reported by Mysyk and Edwards (1985):	
Loss-on-ignition	46.12–47.23%
CaO	29.71–35.72%
MgO	15.34–20.59%
Al_2O_3	0.49–1.42%
Fe_2O_3	0.56–1.00%
SiO_2	0.34–2.52%
Insoluble residue	0.06–0.26%
Na_2O	0.57–0.98%
K_2O	0.03–0.06%
S	<<0.01%

[1] megapascals

Bentonite was recognized as a potentially valuable industrial clay as early as the work by Spence (1924), who reported and described occurrences in the Pasquia Hills, near Eastend, and near St. Victor. Worcester (1937a, b, 1938) conducted the first serious work on these deposits. Discovery of major oil reserves in western Canada in the 1940s and 1950s heightened interest in the bentonite. Much of the research on this resource was conducted during the 1950s by Tomkins (1952) and Tomkins *et al.* (1954).

The value of industrial clays produced in Saskatchewan peaked in 1989 at more than $10 million, but has declined to $1 to 2 million per year with the closing of the province's brick plants and decreased production of bentonite. The geology, development and production of the province's more significant clay resources are discussed below and summarized in Table 16. A more extensive review of Saskatchewan's industrial clay resources is presented in Guliov (2002a).

Bentonite

Bentonite is the commercial term for clay minerals of the smectite group. Sodic bentonite has high cation-exchange capacity and swells to many times its dry volume when wet. These and other properties render it useful for many industrial applications, including fining (clarifying) agents for beer and wine, animal feed

Table 15 – Engineering characteristics of potential Saskatchewan building-stone products (data from Pearse and Guliov, 1996). Locations shown in Figure 61.

Stone prospect	Map ID	Compressive strength (MPa)		Absorbtion (wt. %)	Specific gravity	Modulus of rupture (Mpa)	
		Dry	Wet			Dry	Wet
Neyrinck Lake gabbro-diorite:							
Dark phase	N	246	247	0.03	2.73	15	15
Medium phase	N	217	178	0.07	2.77	16	15
Light phase	N	249	178	0.17	2.71	13	10
Johnson Lake–Pelican Narrows–Deschambault Lake area:							
Johnson Lake Grey Granite	I	101.4		0.6			
Malign Lake Ornamental Black	J	114.2		0.4			
Jan Lake Ornamental Black	K	127.6		0.41			
Sahli Green granite (charnockite)	M	141.0		0.5			
Sahli Red granite	L	107.0		0.68			
Deschambault-Limestone lakes dolomite	O	187.8	134.2	0.58	2.78	20.2	14.2
Creighton-Amisk area:							
McNally Lake Buff marble (dolomite)	A	162.0		0.05			
Amisk Lake Red marble (dolomite)	B	87.0		0.61			
McRobbie Lake Red granite	D	137.6		0.38			
Mystic Lake 'verde antique' (amphibolite) – 1st set	E	186.5		0.26			
Mystic Lake 'verde antique' (amphibolite) – 2nd set	E	132.1		0.26			
Milky Way granite	F	218.0		0.01			
Denare Red granite	H	134.8		0.48			

binder, pond liners, drilling-mud thickener, absorbents (e.g., kitty litter), foundry mouldings and many others.

The Cretaceous Bearpaw Formation, a thick marine mudstone, is subdivided into 11 members (Caldwell, 1968), including the Snakebite Member, which occurs just above the midpoint in the Bearpaw sequence. Predominantly dark grey mudstone, the Snakebite Member is well exposed along Blackfoot Ridge in the Truax-Avonlea area, where up to four beds of swelling bentonite occur near surface in thicknesses ranging from 30 to 76 cm. The bentonite beds are thicker in the Truax-Avonlea area than in the type section of the Snakebite Member on Snakebite Creek. Solution of underlying Paleozoic salts and the development of local basins in the Bearpaw Sea during Snakebite time may explain the local thickening of the bentonite beds (Monea, 1984; Guliov, 2002a).

Exploration for and evaluation of bentonite by industry commenced in earnest during the early 1970s when Contrex Ltd., Flin Flon Mines Ltd. and Inland Cement

Table 16 – Summary of Saskatchewan's main clay resource areas (from Guliov, 2002a).

Area	Location[1]	Age	Remarks
Na-bentonite[2]:			
Truax	6-12-21-W2	U. Cret.	Bearpaw Fm.
St. Victor to Pickthall	4 & 5-6-29-W2 to 33-5-30-W2	Tertiary	Ravenscrag Fm.
Ca-bentonite:			
Knollys	17-6-22-W3	U. Cret.	Battle Fm.
Pelly	5-34-31-W1	U. Cret.	Vermillion River
Moosomin	NW-12-31-W1	U. Cret.	Riding Mountain Fm.
Kaolin[2]:			
Gollier Creek	17 to 20-5-2-W3	U. Cret.	Whitemud Fm
Wood Mountain	9-5-4-W3	U. Cret.	Whitemud Fm
Willows	33-7-28-W2	U. Cret.	Whitemud Fm
Eastend Frenchman River	6-7-21-W3; 35-5-20-W3	U. Cret.	Whitemud Fm
Refractory[2]:			
Dirt & Cactus Hills	13 & 24-13-26-W2; 24 & 28-12-24-W2	U. Cret.	Whitemud Fm
Flintoft	26-5-3-W3	U. Cret.	Whitemud Fm
		U. Cret.	Whitemud Fm
Ball[2]			
Willows-Readlyn	1-8-29-W2; 7-8-28-W2; 28,29,32 & 33-7-28-W2	U. Cret.	Whitemud Fm
Willow Bunch	21-7-28-W2	U. Cret.	Whitemud Fm
	12-6-28-W2	U. Cret.	Whitemud Fm
Stoneware[2], earthenware[2]:			
Eastend	6-7-21-W3; 3-6-22-W3	U. Cret.	Whitemud Fm
Ravenscrag	28 & 34-6-23-W3	U. Cret.	Whitemud Fm
Flintoft	27-5-3-W3	U. Cret.	Whitemud Fm
Willow Bunch	14,15,22 & 23-5-28-W2	Tertiary	Ravenscrag Fm.
Rockglen	10,14 & 15-3-1-W.	Tertiary	Ravenscrag Fm.
Strathallan	6-2-2-W3	Tertiary	Ravenscrag Fm.
Willow Bunch	12-6-28-W2, 12-7-28-W2; 15-5-28-W2	Tertiary	Ravenscrag Fm.
Harptree	5-4-26-W2	Tertiary	Ravenscrag Fm.
Bonneau Lake	3 & 10-5-27-W2	Tertiary	Ravenscrag Fm.
Estevan	10, 13 & 15-2-8-W2	Tertiary	Ravenscrag Fm.
Goodwater	24-6-13-W2; 26-5-11-W2	Tertiary	Ravenscrag Fm.
Common clays[2]:			
Widespread in glaciolacustrine deposits in southern Saskatchewan		Quaternary	Pleistocene-Recent; includes bentonitic-illitic and mixed layer clays

[1] Dominion Land Survey system co-ordinates (section, township, range, meridian)

[2] indicates past and/or present development

Industries Ltd. engaged in field and laboratory work on the Bearpaw bentonites in the Truax area. The investigations, in which Inland Cement Industries Ltd. and the Saskatchewan Research Council played an important part, culminated in the establishment by Avonlea Mineral Industries Ltd. of a bentonite quarry near Truax and an 80 000 t/y processing plant at Wilcox in 1978. Avonlea operated the quarry and plant until 1990, and the operation was resumed by Canadian Clay Products Inc. in early 1991. Canadian Clay is currently the only bentonite producer in Canada (Figure 62). They mine about 15 000 t of raw bentonite each summer and produce a variety of products for feed pellets, sulphur-fertilizer prills, civil-engineering applications, foundry-sand binder, drilling and absorbents (Jones, 2002).

Swelling bentonites also occur in the Tertiary Ravenscrag Formation, and are exposed in the area extending from Willow Bunch and St. Victor westward to Twelve Mile Lake. The bentonite is exposed in many erosional 'spurs' along valley walls, and is especially well exposed just west of the village of St. Victor. Inland Cement Industries Ltd. conducted extensive field and laboratory investigations on Tertiary bentonites in the St. Victor area, including some 200 exploratory boreholes. The primary bentonite seam varied in thickness from 0.3 to 5.2 m. The ratio of overburden thickness to seam thickness varied from less than 1 in valleys to 20 or more at higher elevations along the flanks of the valleys. Laboratory testing for applications such as pelletizing taconite, drilling mud and foundry-sand bonding agent showed the properties of the bentonite to be quite variable across the area of investigation (Guliov, 2002a).

Calcium or nonswelling bentonites find industrial application in decolourizing oils, catalysts in petroleum cracking and absorbents. Nonswelling bentonite has been documented in Late Cretaceous and Tertiary strata in the vicinity of Pelly, Moosomin, Rockglen and Eastend, but little is known of the properties or extent of these occurrences (Winer, 1954; Guliov, 2002a).

Ceramic Clays

Kaolinitic clays from the upper Cretaceous Whitemud Formation and the Willowbunch Member of the Tertiary Ravenscrag Formation have been exploited in the manufacture of face brick, refractory brick, pottery, flue tile, tableware and a host of other products. There are two current producers. I-XL Industries quarries Whitemud clay on a campaign basis to supply their brick plant in Medicine Hat, Alberta. Plainsman Clay Ltd. quarries stoneware clay from the Whitemud Formation near the community of Ravenscrag. From their plant in Medicine Hat, Plainsman markets pottery-clay bodies to artisans across North America (Plainsman Clays, 2001).

The Upper Cretaceous Whitemud Formation is a sequence of terrigenous kaolinitic sands, clays and sandy clays that outcrop as extensive erosional remnants from the Cypress area in the west to the Big Muddy Valley in the east. Smaller outliers are present near Halbrite, Claybank and in the Vermillion Hills. The important deposits are those in the Eastend-Shaunavon, Wood Mountain–Willow Bunch and Claybank districts. All are kaolinitic, but they vary widely in physical and chemical properties, which affects their prefiring and firing characteristics, and thus their ultimate application.

Clays of the Willow Bunch Member in the Tertiary Ravenscrag Formation are kaolinitic, lower grade ceramic clays and smectite. The kaolinite-based clays occur high in the formation and are exposed or lie near the surface in the dissected upland region south of the Big Muddy Valley system, especially south of Big Muddy Lake, west and north of Big Beaver, southwest of Harptree, and south and west of Willow Bunch, Rockglen, Strathallen and the uplands southeast of Wood Mountain. The clays are suitable for earthenware and stoneware, firing to maturity at lower average temperatures than Whitemud clays, in part because of a higher alkali content.

With a few exceptions, the clay industry during the early decades of the 20th century consisted of numerous small plants producing mainly common brick for the local market. Most utilized local glaciolacustrine clays. Some of the larger plants, such as the Saskatchewan Clay Products Co. (later the Dominion Fire Brick and Clay Products Co.) at Claybank, the Estevan Coal and Brick Co. and the Bruno Clay Works Ltd., had diversified to include face brick, drain tile, structural tile or fire brick.

The Claybank brick plant commenced operation in 1911 with the production of common and face brick utilizing Whitemud clays. In a short time, as the construction brick market declined, the plant switched to

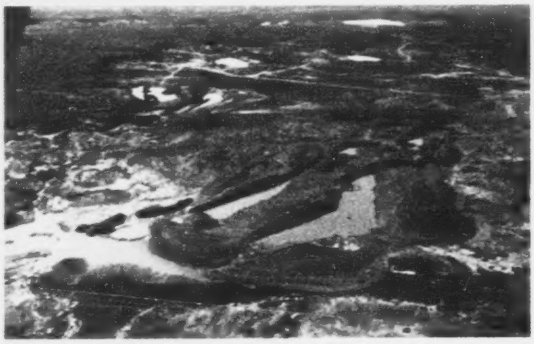


Figure 62 – Canadian Clay Products Inc. bentonite quarry near Truax.

refractory products and was the only plant to produce refractories in the province. The plant was taken over by A.P. Green (Canada) Ltd. in about 1955 and devoted exclusively to production of refractory brick until it closed in 1989. Refractory bricks from the Claybank plant lined the fire boxes of Corvette warships and CN and CP locomotives. The fire brick was also used in the construction of the rocket launch pads at Cape Canaveral. The brick plant is one of the best preserved examples of early 20th century industrial activity in Canada, and was declared a National Historic Site in 1994. (Claybank Brick Plant Historical Society, 1998).

The Estevan Coal and Brick Co. (probably the former Eureka Coal and Brick Co.) commenced operations in about 1913 and was taken over in 1925 by International Clay Products Ltd. The company produced common and face brick by the dry-press and stiff-mud techniques and, in 1925, developed a stiff-mud textured face brick. In 1944, the plant was purchased by the Crown and became the Clay Products Division of Saskatchewan Minerals Corporation. Later, the company became Estevan Brick Ltd., although ownership has changed several times. I-XL Industries, a major western Canada brick producer, bought Estevan Brick in 1996. The Estevan plant has been on a care-and-maintenance basis since then, but I-XL continues to quarry clay from southwestern Saskatchewan for brick manufacture at their Medicine Hat plant.

Ball clays of the Whitemud Formation have been mostly exported from the province. The high-quality light-burning clay was mined since the mid-1920s. Early production came from surface workings at the Midland mine near Willow Bunch between 1925 and 1932. Later, as easily available material was depleted, an adit was driven into the hillside and underground mining continued until the operation closed in 1941. Stoneware clays and ball clays from the Willows-Readlyn area found a market in whiteware potteries in Ohio and, for many years, with Medalta Pottery in Medicine Hat, which played a significant role in supplying the armed forces with tableware during World War II. The white-firing ball clays with their high plasticity were used as bonding agents to provide high green strength for less plastic clays. Whitemud stoneware clays from the Eastend and Willows areas were used for this purpose. These stoneware clays had also found a market in structural ware and sewer-pipe production in Medicine Hat by Medicine Hat Brick and Tile Co., in the Regina plant of Western Clay Products Ltd. (a division of I-XL Industries Ltd.) and in face-brick production at Estevan. High-quality, white-firing ball clays were employed by Estevan Brick, particularly in white-brick production.

Kaolin

Kaolin is commonly used as both filler and coating material in high-quality and coated papers. The expansion of the paper industry in the northwestern United States and western Canada has spurred periodic bouts of intense interest in Saskatchewan's kaolin deposits since the mid-1980s. In addition to paper markets, potential opportunities have been identified in fillers and extenders in plastics, rubber products, paints, adhesives and as feedstock for the production of aluminum metal and synthetic zeolites (Guliov, 2002a).

The principal kaolin resource is the kaolinized sand at the base of the Whitemud Formation (Figure 63). Utilization of the sandy, kaolinized, basal beds of the Whitemud has thus far been limited to blending with plastic clays to enhance their refractory properties and reduce drying shrinkage in brick production. The high kaolinite content of the Whitemud sands, ranging from about 45% to more than 60% in the Wood Mountain area, has attracted a considerable amount of attention in the last 40 years. Studies have been directed at resource definition, mineralogical characterization, sand-clay separation, technology, stratigraphy and alumina content for potential aluminum production, refractory materials and kaolin filler. Of note are the investigations by the Canada Department of Mines and Resources (1948), Carlson and Babey (1955), Spyker *et al.* (1954), Brady (1962), and unpublished work of the Saskatchewan Research Council.

Hudson (1967) reported that the Wood Mountain kaolin is about 50% less than 2 µm in size and has a reflectance (a measure of the percentage of the incident light reflected by the sample) value of about 70%. Standard bleaching tests had failed to improve the whiteness. It was deduced, from laboratory examination, that the colouration was likely due to iron in solid solution with kaolin. More recent investigations by the Saskatchewan Research Council have identified smectite and extremely fine ilmenite as the main agents of colouration. Differential flocculation and high-intensity wet magnetic separation combined with chemical bleaching have succeeded in raising the reflectance to values in excess of 80%. The work represents a significant milestone in

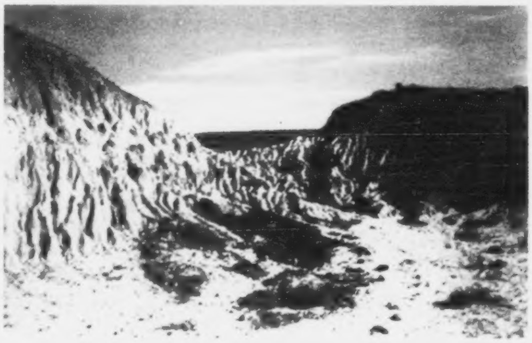


Figure 63 – Kaolinized sand of the Whitemud Formation, Wood Mountain area.

Whitemud kaolin investigations, by helping to dispel misconceptions regarding its potential value in the filler industry.

Beginning in 1984, Ekaton Industries Inc. had conducted exploration and evaluation of kaolin resources in the Eastend and Wood Mountain areas, and proposed to develop the Gollier Creek deposit (Master, 1987). The company excavated several thousand tonnes of kaolinized sand for processing at a pilot plant near Regina. Success was reported in upgrading the kaolin to paper filler standards. Calcining tests were also reported as successful. The company went into receivership in about 1990 before it could develop the kaolin resources, and the pilot plant and equipment fell into disuse. Testing of beneficiated samples from the Ekaton pilot plant was conducted for the Saskatchewan Geological Survey by English China Clays, PCL (ECC), one of the world's leading producers of kaolinitic clays. They concluded that additional beneficiation to remove iron and titanium was required to improve the colour and reflectance of the kaolin. In ECC's opinion, such treatment might render the kaolin competitive, even in the fine filler grades (English China Clays PCL, 1994; Guliov, 2002a).

In 1992, Kaolin Industries Ltd. (KIL) of Saskatoon acquired the Ekaton plant equipment and conducted testing of new patented technology relating to silica removal, brightening, calcining and kaolin delamination. The company reported success in producing low-brightness, calcined, coating-grade kaolin; noncalcined, low-brightness filler; high-brightness, calcined filler; and medium-brightness, delaminated kaolin (Kaolin Industries Ltd., 1994). Production of high-brightness, coating kaolin was not achieved; according to KIL, the high content of very fine silica was a major stumbling block. Only small quantities of finished kaolin products were produced in the KIL pilot plant and the company's affairs were wound down in the mid-1990s, but interest in the Whitemud kaolin persists. At least two parties have mounted active exploration and beneficiation campaigns since 1998.

Bloating Clay

Quaternary glaciolacustrine clays were utilized by many small brickyards across Saskatchewan, at least since 1908 when the Bruno Clay Works Ltd. commenced operation. Worcester (1950) recorded 26 individual brickworks that had operated at one time or another in widely scattered areas of the province up to 1950. Many fell victim to a variety of problems, including small local markets, a lack of working capital, poor or inadequate raw materials and insufficient technical and business skill.

During the 1950s, a considerable amount of research was conducted on the bloating characteristics of Quaternary clays and Cretaceous marine shales and their use in the production of light-weight aggregates for concrete. Of note is the work by the Canada Department of Mines and Technical Surveys and by Sacuta (1956). Plants in Regina and Saskatoon produced such aggregates from local clays. The Regina plant closed in about 1990, and the Saskatoon plant is operated only on a campaign basis, mining and processing a few thousand tonnes every few years. The clay is fired in rotary kilns to temperatures in the range of 1036-1120°C (Hudson, 1984) until the evolving gas bubbles become entrained within the glassy mass of thick molten clay. Cooling is timed so that the fused product is frozen in a highly porous state. The porous, low absorption, light-weight product is used in manufacturing concrete construction blocks for local markets. The bulk density of the finished product is in the range of 600 to 1100 kg/m^3, compared to 2000 kg/m^3 or more for conventional granular aggregate.

Local glaciolacustrine clays were also used as a source of aluminosilicate for cement production by Inland Cement Industries Ltd. in Regina until the cement plant closed in 1992.

Naturally-Fired Clay (Clinker)

Rocks above and below coal seams are altered by *in situ* combustion of the coal. The combustion may be spontaneous or induced by wildfires or lightning. The mudstones of the Ravenscrag Formation are thermally altered up to and including fusion. Locally termed 'clinker' or 'scoria', this material is found throughout the outcrop belt of the Ravenscrag Formation coals. The buff-, brown-, salmon- and maroon-coloured clinker is quarried and crushed for use as decorative landscape rock and to control mud on paths and baseball infields. Boulders are marketed as ornamental blocks for rock gardens (Guliov, 1995; Guliov, 2002b).

Diamonds

The central Saskatchewan kimberlite province, consisting of more than 70 *in situ* bodies, is one of the largest diamondiferous kimberlite provinces in the world (Scott-Smith *et al.*, 1995). The bulk of the bodies are located in the Fort à la Corne (FALC) kimberlite field, a north-northwest-trending linear zone measuring 50 km long and 15 km wide (Figure 64). Several satellite clusters, including the large Snowden cluster to the northeast, the Foxford and Weirdale kimberlites to the northwest and the Candle Lake kimberlites to the north, are also north-northwest trending.

General Geology of Kimberlites

Diamonds form in the mantle beneath unusually thick, cool, continental-shield regions older than 2.5 Ga (Clifford, 1966). Kimberlites, the main primary source of diamonds, are volatile-rich ultrabasic rocks that form within the asthenosphere at depths in excess of 150 km. During ascent toward the surface, kimberlitic magmas may sample diamondiferous rocks below a thick continental keel. The diamonds within the kimberlite occur as sparse (0 to 1.4 ppm) xenocrysts and in mantle xenoliths within the kimberlite matrix (Kjarsgaard, 1996).

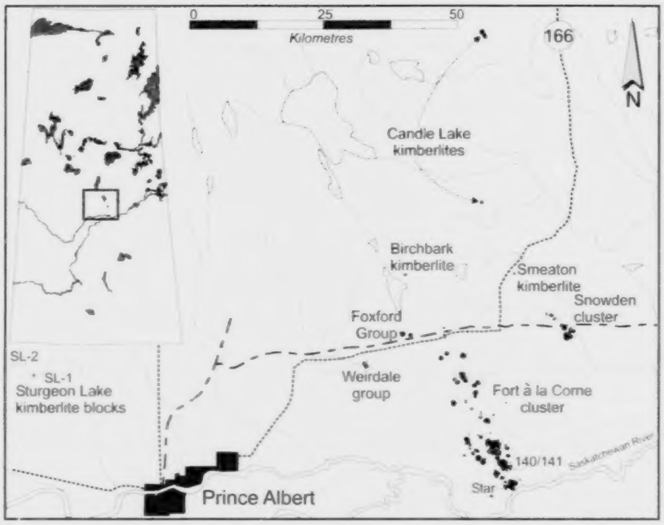


Figure 64 – Locations of central Saskatchewan kimberlites.

Kimberlites are traditionally divided into three facies, based predominantly on South African kimberlites: crater, diatreme and hypabyssal (Figure 65). The crater facies consists of pyroclastic deposits and resedimented volcaniclastics within a crater. The diatreme facies consists mainly of tuffisitic kimberlite breccias that are homogeneous compared to the crater- and hypabyssal-facies rocks. With increasing depth, diatreme-facies rocks grade into hypabyssal-facies rocks, comprising dikes, 'blows' and sills, in the root zone of the diatreme (Kjarsgaard, 1996). The degree of erosion exposes variable levels of kimberlite (Figure 65). Preserved crater-facies kimberlites are very rare, as most are eroded subsequent to formation, although they represent important, moderate- to high-grade and high-tonnage deposits in a few cases (e.g., Orapa and Jwaneng, Botswana; Kjarsgaard, 1996).

Geology of Saskatchewan Kimberlites

In the Fort à la Corne area, the Phanerozoic succession, in excess of 700 m thick, unconformably overlies Archean and Paleoproterozoic basement rocks of the Sask Craton. The crystalline basement rocks consist of schist, orthogneiss and local banded iron formation (Collerson *et al.*, 1989). Neodymium model ages for basement rocks from the area indicate mantle separation ages of 3.12 to 2.35 Ga (Collerson *et al.*, 1989), whereas crustal xenoliths from kimberlites have been dated between 3.2 and 2.1 Ga (Davis *et al.*, 1998). The basal part of the Phanerozoic section comprises 400 m of Paleozoic mixed marine clastic and carbonate rocks. These are overlain by about 200 m of Lower Cretaceous Mannville Group and Colorado Group sedimentary rocks that host the kimberlites (Figure 66). These strata consist of the predominantly continental to marginal-marine Mannville Group (Cantuar and Pense formations) and the predominantly marine lower Colorado Group (Joli Fou, Westgate and Belle Fourche formations; Zonneveld *et al.*, 2002). The Mannville–lower Colorado contact reflects a regional marine transgression. The Phanerozoic rocks are overlain by 70 to 120 m of Pleistocene glacial sediments.

Radiometric dating and stratigraphic relationships indicate that the kimberlites range in age from approximately 105 to 94 Ma (Leckie *et al.*, 1997), with earlier kimberlites possibly as old as 119 Ma (Scott-Smith *et al.*, 1995). The kimberlites are different from most others worldwide in that they are dominantly composed of 'crater-facies' volcaniclastic rocks (Lehnert-Thiel *et al.*, 1992; Scott-Smith *et al.*, 1994). These rocks consist of pyroclastic lapilli- and olivine-dominated tuffs, local debris flows and reworked volcaniclastic kimberlite (Kjarsgaard *et al.*, 1995; Leckie *et al.*, 1997; Jellicoe *et al.*, 1998; Kjarsgaard *et al.*, 2002), all of which are interstratified with Lower Cretaceous (Albian) marine, marginal-marine and continental sedimentary rocks. The existence of subvolcanic rocks, representing hypabyssal intrusives and feeder vents, was problematic until a vent was drilled to a depth of 627 m in January 2001. Diatreme- and hypabyssal-facies kimberlite were encountered in the lower parts of this drill intersection (Challis and Marcia, 2001).

In the Fort à la Corne area, these bodies are classified by mineralogy as Group I kimberlites, characterized by two generations of olivine in a groundmass of monticellite, spinel, perovskite, serpentine and carbonate (Lehnert-Thiel *et al.*, 1992; Scott-Smith *et al.*, 1994; Jellicoe *et al.*, 1998). Most of the kimberlites contain mantle-derived (peridotitic and eclogitic) xenoliths and xenocrysts (e.g., garnet, chromite), along with crustal xenoliths consisting of Precambrian basement and Phanerozoic cover-sequence rocks.

Pyroclastic kimberlite is generally composed of variable proportions of two end-member rock types: 1) juvenile lapillistone airfall deposits, and 2) olivine crystal-tuff airfall deposits (Figure 67). Sorting is recognized and graded bedding is common. These deposits are likely the result of several styles of eruption due to variations in volatile content and degree of groundwater interaction (Leckie *et al.*, 1997; Jellicoe *et al.*, 1998).

Both subaerial deposits and airfall deposits into shallow water have been recognized (Leckie *et al.*, 1997).

Studies reveal that volcanism may initially have been of the violent Stromboli type, driven by magmatic volatiles and/or phreatomagmatic processes (Scott-Smith *et al.*, 1995; Leckie *et al.*, 1997). This type of volcanism may be associated with lapilli-rich airfall tuffs. The lapilli tuffs are generally clast supported, with juvenile lapilli morphology ranging from spherical, ovoid, flattened, moulded and amoeboid to locally vesicular (Scott-Smith *et al.*, 1996; Leckie *et al.*, 1997; Jellicoe *et al.*, 1998). The groundmass has been variably quenched, with the interclast matrix typically consisting of serpentine and/or carbonate and magnetite (Scott-Smith *et al.*, 1995).

Subsequent volcanism may have evolved into a more violent eruptive style, with deposits dominated by olivine crystal tuffs (Scott-Smith *et al.*, 1995; Leckie *et al.*, 1997). These deposits may have formed due to 1) the kimberlitic magma being olivine rich; and/or 2) high magma fragmentation, resulting in juvenile material forming ash-sized particles, which were winnowed out of the eruption cloud and redistributed downwind, leaving the olivine crystals to dominate proximal airfall (Scott-Smith *et al.*, 1995; Leckie *et al.*, 1997).

Pyroclastic kimberlite is thought to have been reworked in both terrestrial and marine environments (Leckie *et al.*, 1997; Zonneveld *et al.*, 2002). During Mannville sedimentation, kimberlite was fluvially reworked and deposited in deltaic to marginal-marine settings as kimberlitic sandstone and conglomerate. In contrast, younger kimberlites (lower Colorado age) were wave reworked in distal to proximal offshore and offshore-onshore transitional settings (Zonneveld *et al.*, 2002).

The shape of central Saskatchewan kimberlites is very different from the classical carrot-shaped diatreme observed in South Africa (Figure 65). Body architecture ranges from simple, mono-eruptive bodies to stratigraphically complex, multi-eruptive structures marked by stacking of lensoid eruptive deposits (Jellicoe *et al.*, 1998). The gross morphologies of Saskatchewan kimberlite bodies have been characterized as pancake- or sheet-like (Lehnert-Thiel *et al.*, 1992), saucer or champagne-glass shaped (Scott-Smith *et al.*, 1994), marine-reworked and -truncated tephra cones (Leckie *et al.*, 1997) and stacked disks (Jellicoe *et al.*, 1998).

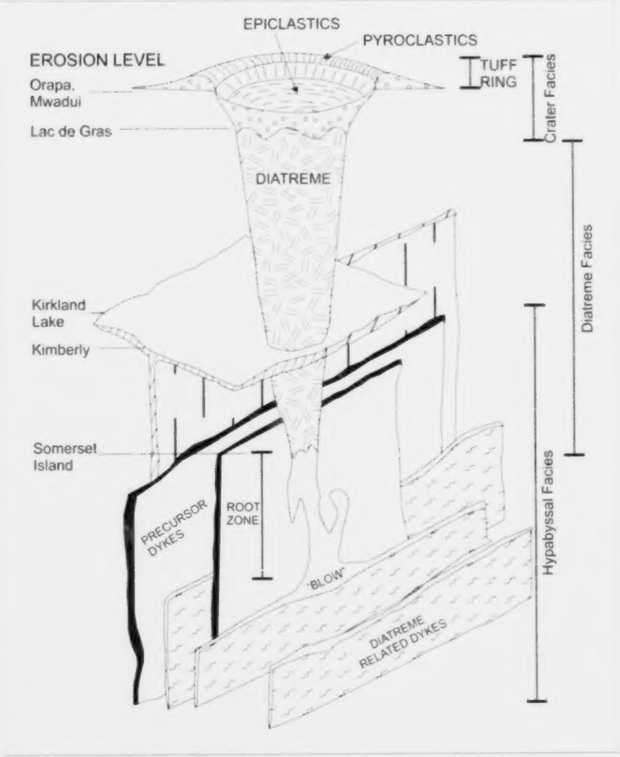


Figure 65 – Generalized model of the classic South African–type kimberlite magmatic system, illustrating the relationships between crater-, diatreme- and hypabyssal-facies rocks (from Mitchell, 1986). Also shown are the present erosion levels of some representative economic and Canadian kimberlites (from Kjarsgaard, 1996). Contrast this with the models presented for Saskatchewan kimberlites in Figure 68.

There are two models for central Saskatchewan kimberlite emplacement, with marked contrasts in the timing and mode of emplacement and the degree of kimberlite resedimentation (Figure 68). Scott-Smith *et al.* (1995) proposed a precursor stage (approx. 119 to 100 Ma) of pyroclastic kimberlite volcanism occurring as a number of small (<5 m thick), conformable, non-reworked bodies deposited in a coastal marine, subaerial plain environment congruent with deposition of Mannville sandstones (Figure 68a). A transgression of the Cretaceous seaway resulted in lower Colorado, predominantly shale sedimentation (approx. 100 to 91 Ma). A short-lived regression (94 to 91 Ma) gave way to the main period of subaerial kimberlite volcanism and development of very large kimberlites (approx. 97.5 to 91 Ma). This stage of volcanism is thought to have involved a two-phase process. Here, the near-surface interaction of kimberlitic magma and a saturated aquifer (the Mannville) prompted phreatomagmatic crater excavation. This was followed by a magmatic eruptive phase in which pyroclastic volcanism and minor resedimentation infilled the crater. This two-stage process was suggested to account for the

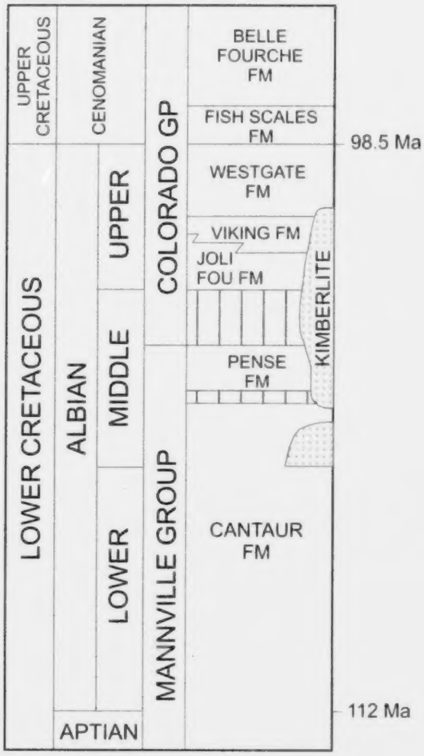


***Figure 66 – Stratigraphic position of the central Saskatchewan kimberlites. Vertical hatched pattern represents missing sections of the stratigraphic record* (modified from *Kjarsgaard, 1995*).**

champagne-glass shape of the Fort à la Corne kimberlites. Following volcanism, the Cretaceous seaway again transgressed over the entire region, accompanied by deposition of upper Cretaceous mudstones.

The second model, proposed by Leckie *et al.* (1997), begins with the eruption of older (>101 Ma, Mannville-age) kimberlite airfall deposits within a delta-plain environment, and subsequent fluvial resedimentation that resulted in kimberlitic sandstone and conglomerate deposits (Figure 68b). This was followed by the main period of kimberlite volcanism (ca. 101 Ma). Initial volcanism was driven by exsolved magmatic volatiles and/or interaction with groundwater (phreatomagmatism). Variation in the degree of volatile exsolution and/or interaction with groundwater resulted in variable vent development. Subsequently, multiple phases of kimberlite pyroclastic airfalls were deposited conformably (initially on terrestrial strata of Albian age) to form positive-relief tephra cones in lower Colorado Group time. Marine transgression, associated with deposition of Westgate Formation shales, inundated and bevelled the tephra cones, creating the present pancake morphology of the kimberlites (Leckie *et al.*, 1997).

More recently, the problem of subaerial kimberlite volcanism during marine sedimentation of the Pense, Joli Fou, Westgate and Belle Fourche formations (i.e., during a period of sea-level highstand) was examined by Kjarsgaard *et al.* (2002). They suggested that the Fort à la Corne area was an island within the Cretaceous interior seaway from at least ca. 103 Ma (top of the Cantuar Formation) onward. Existence of an island allows for simultaneous deposition of pyroclastic subaerial kimberlite airfall deposits on the island and offshore marine mud in the interior seaway.

In general, the observation that 'individual' kimberlite geophysical anomalies consist of multiple stacked kimberlite bodies of differing stratigraphic assignments and ages (plus their reworked equivalents) and the occurrence of coalescing eruptive centres have resulted in 'individual' kimberlite bodies with extremely complex internal geometries (Kjarsgaard *et al.*, 2002). Seismic surveys have improved the geophysical modelling of the kimberlite complexes (Figure 69).

Central Saskatchewan kimberlite bodies vary greatly in size, with some ranking among the largest in the world. Drilling and geophysical modelling have led to body-size estimates ranging from 3 to 930 million t (Jellicoe and Marcia, 2002), covering areas between 3 and 250 ha. Approximately 70% of the kimberlites are diamondiferous (Jellicoe and Marcia, 2002), and approximately 50% contain macrodiamonds with at least one

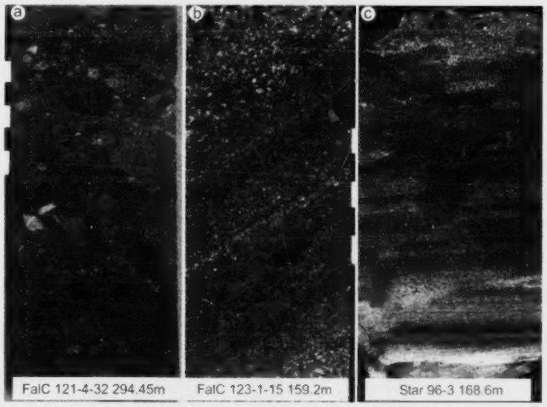


***Figure 67 – Fort à la Corne core samples: a) xenolithic breccia composed of massive, densely packed, medium- to coarse-grained olivine with common garnet and distinct xenoliths of mantle, basement and county rock* (from *Jellicoe et al., 1998); b) bedded kimberlite with 0.5 to 1.5 cm thick beds composed of very fine to fine-grained olivine separated by 1 to 3 cm thick beds of fine- to medium-grained olivine lapilli pyroclastic kimberlite* (from *Jellicoe et al., 1998); scale in centimetres; c) reworked kimberlitic sandstone exhibiting low-angle cross-stratification and soft-sediment microfaulting* (photo by *J-P. Zonneveld, courtesy of Shore Gold Inc.*).**

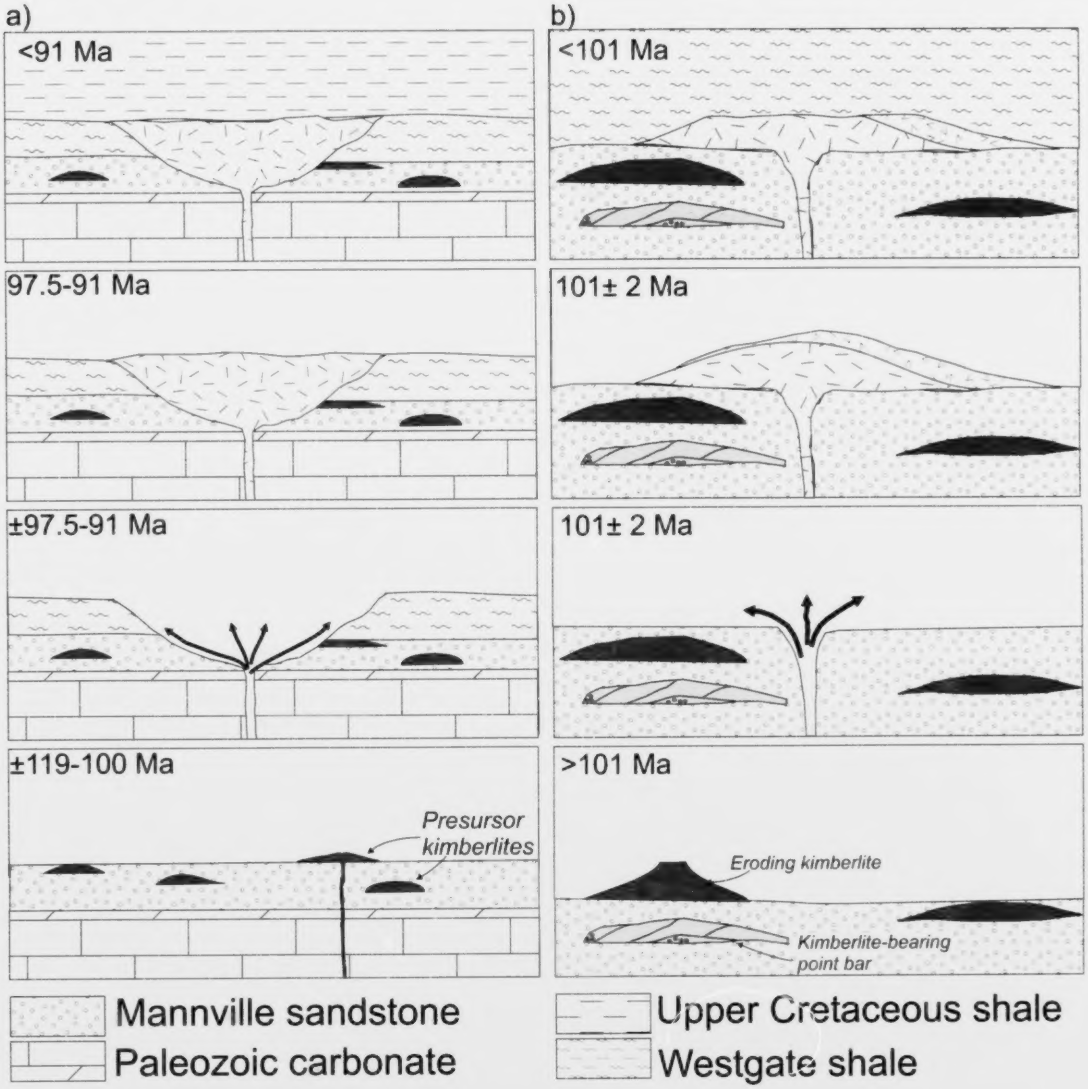

a)
<91 Ma
97.5-91 Ma
±97.5-91 Ma
±119-100 Ma
Presursor kimberlites
b)
<101 Ma
101± 2 Ma
101± 2 Ma
>101 Ma
Eroding kimberlite
Kimberlite-bearing point bar
Mannville sandstone
Paleozoic carbonate
Upper Cretaceous shale
Westgate shale

Figure 68 – Contrasting emplacement models for Fort à la Corne kimberlites: a) Scott-Smith* et al. *(1995) have proposed precursor kimberlite formation followed by main kimberlite eruption. Initial phreatomagmatic crater (maar) formation was followed by a later pyroclastic crater infill and seaway transgression associated with deposition of Upper Cretaceous shale. b) Leckie* et al. *(1997) have proposed eruption and erosion of Mannville-aged kimberlites, followed by the main period of kimberlite volcanism. Initial violent volcanism was driven by exsolved magmatic volatiles and/or interaction with groundwater (vent development highly variable). This was followed by magmatic volcanism and development of positive-relief tephra cones. Seaway transgression was associated with bevelling of kimberlite tops and deposition of Westgate shale.

dimension greater than 1 mm. Close to 70% of the recovered macrodiamond population from the kimberlites of the Fort à la Corne Joint Venture are considered to be gem-quality stones (Jellicoe *et al.*, 1998). Estimates of diamond grade vary, with some of the more prospective kimberlites approaching and exceeding 20 carats per hundred tonnes (cpht). Much of the work in the past few years has focused on assessment of the economic potential of known diamondiferous kimberlite bodies, predominantly by the extraction of bulk samples using large-diameter (24-inch), reverse-flood, air-lift–assist drillholes.

Exploration History

The first recorded diamond-exploration activity in Saskatchewan occurred in 1948 when Johnny Johnson reported the discovery of five diamonds in the Prince

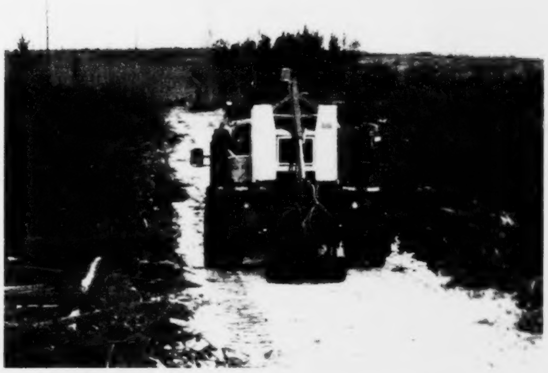


Figure 69 – Seismic survey of the Star and 140/141 kimberlites in the Fort à la Corne district provides data for improved modelling of the character and genesis of kimberlite bodies.

Albert area, although this find was never confirmed. In 1961, Max Pellack claimed to have recovered two diamonds (about 0.6 cm in diameter) in gravels 9.6 km west of Prince Albert. Once again, this claim was unsubstantiated, although Dr. Mouseau Tremblay of Canadian Rock Co. Ltd. (a De Beers Canadian subsidiary) toured the area and retrieved glacial samples that yielded minerals of kimberlitic affinity.

The modern resurgence in diamond exploration in the province began in 1988. Between 1990 and 2001, close to $60 million were spent on diamond exploration in Saskatchewan (Figure 70). This exploration has been relatively cyclic in nature, with expenditures and the number of claims increasing in the early 1990s, peaking in 1993 with more than $10 million spent on exploration and 2500 new claims covering over 1.4 million ha. The greatest concentration of activity has covered 1) the region south of La Ronge, extending from the Wapawekka Hills to the Smoothstone Lake area; 2) the Montreal Lake area, along the eastern flank of Prince Albert National Park; 3) the Prince Albert–Melfort–Nipawin region; and 4) south-central and southwestern Saskatchewan, particularly in the Mankota–Wood Mountain–Scout Lake area southward nearly to the United States border. Since 1998, a significant resurgence in diamond exploration has occurred in Saskatchewan, largely due to encouraging diamond results from the Fort à la Corne Joint Venture.

The discovery of kimberlite by Monopros Ltd., a De Beers Canadian subsidiary, near Sturgeon Lake, some 30 km northwest of Prince Albert, in 1988 initiated the modern era of diamond exploration in Saskatchewan (Figure 64; Scott-Smith *et al.*, 1995; Kjarsgaard, 1995). The discovery proved to be a rootless, ice-rafted block. By May 1989, Claude Resources Inc. had announced the discovery of a second ice-rafted kimberlite block 4 km northwest of the Sturgeon Lake discovery. Enticed by rumours of the Sturgeon Lake discovery, Uranerz Exploration and Mining Ltd. examined a series of Geological Survey of Canada regional aeromagnetic maps of the area and identified a number of circular anomalies in the Fort-à-la-Corne Provincial Forest, 80 km east of Prince Albert. This was soon followed by a detailed aeromagnetic survey that identified approximately 70 anomalies (Lehnert-Thiel *et al.*, 1992). Since the initial staking and drilling, Uranerz has brought in joint-venture partners Cameco Corporation, De Beers Canada Corporation and Kensington Resources Ltd. This consortium is hereafter referred to as the Fort à la Corne Joint Venture.

The magnetic anomalies in the Fort à la Corne area were delineated as possible kimberlites in the late 1980s, with drill confirmation continuing into the 1990s. In 1993 and 1994, two diamondiferous kimberlites (20 and 50 km north of the main Fort à la Corne trend) were discovered in the Candle Lake area by joint-venture partners Great Western Gold Corporation and War Eagle Mining Co. Inc. In 1996, drilling confirmed another kimberlite body, the Smeaton kimberlite, north of the main Fort à la Corne trend. Consolidated Pine Channel Gold Corporation, United Carina Corporation and Shane Resources Ltd. currently own the Smeaton kimberlite. Also in 1996, Shore Gold Inc. acquired claims released from a Crown Reserve adjacent to the southern end of the Fort à la Corne Joint Venture property. An aeromagnetic survey over the

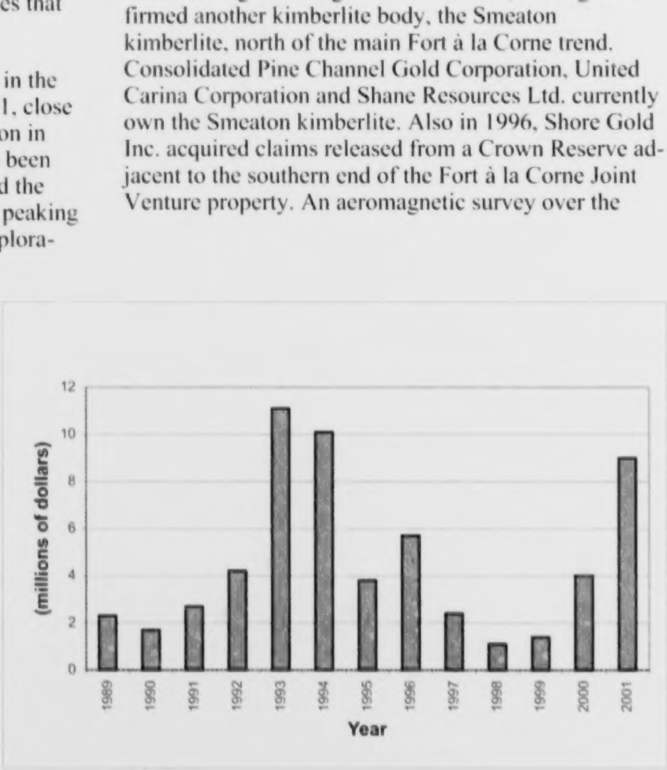


Figure 70 – Saskatchewan diamond-exploration expenditures, 1989-2001.

area led to the discovery of the diamondiferous Star kimberlite.

The Fort à la Corne Joint Venture (De Beers Canada Corporation [42.25%], Kensington Resources Ltd. [42.25%], Cameco Corporation [5.5%] and UEM Inc. [carried 10%]) covers a consolidated property holding that contains 63 drill-tested kimberlite bodies. Since 1990, the joint venture has reported total recovery of 1349 macrodiamonds (>0.8 mm), the largest stone being 1.535 carats in size (1 carat = 0.2 g). At the beginning of 2000, the De Beers' Mineral Resource Evaluation Department (MINRED) reviewed all available macrodiamond and microdiamond data and reprioritized the kimberlites (Gracie and Tourigny, 2001). Priority targets 122 and 141 were selected for bulk sampling by large-diameter (24-inch) reverse-circulation drilling in the 2000 program. A total of 212 macrodiamonds was recovered from body 122, while body 141 yielded 275 macrodiamonds (Figure 71a). De Beers employed a statistical treatment of the sample results to estimate grades (using a minimum 1 mm cutoff size) of between 8 and 13 cpht for body 122, and 19 cpht for body 141.

The 2000 drill program recovered sufficient stones to permit preliminary revenue modelling (Table 17). Ranges in model value are expressed by using conservative, best fit and optimistic models for body 141. Modelled *in situ* value estimates (using standard selling value [SSV] diamond values) for body 141 range from $US90/carat to $US178/carat (>1.5 mm), corresponding to *in situ* gross-value estimates ranging from $US16/tonne to $US32/tonne.

Encouraged by the results from the 2000 program, the FALC Joint Venture partners approved a $4.79 million, two-phase program for 2001 with the main goal of obtaining up to 80 additional carats from body 141, to improve confidence in average diamond-value modelling (Berryman, 2001). In 2001, 16 coreholes and 10 large-diameter holes (9 in body 141 and 1 in body 150) were completed (Figure 71b). A total of 2531 m of kimberlite NQ core was recovered, along with 889 theoretical tonnes of kimberlite sampled by the large-diameter rig (Berryman, 2001).

Work on the large (>200 ha) Star kimberlite (100% owned by Shore Gold Inc.) since 1996 has recovered 1653 diamonds, 269 of which are macrodiamonds with one dimension >0.5 mm (Challis and Marcia, 2001). Including the 2000 and 2001 samples, grade estimates for the body are 36 cpht, or 31 cpht using only macrodiamonds. Some of the most promising grades have come from drillhole Star 020, which intersected 539 m of kimberlite and terminated (in kimberlite) at a depth of 627 m. Sampling of the upper 400 m averaged 61 cpht over 311.6 m, including 116 cpht over 133 m, and 435 cpht over 25.6 m (Challis and Marcia, 2001).

Regional Exploration Potential

It has been well documented that diamondiferous kimberlites are associated with the stable parts of Archean cratons (>2500 Ma; Clifford, 1966). Remobilized Archean cratons or Paleoproterozoic orogenic belts (1600 to 2500 Ma) are favourable for the emplacement of diamondiferous lamproites. Stable cratonic areas are generally characterized by thick, cool, rigid crust with dense upper-mantle keels. These conditions are necessary for the formation and preservation of diamonds within the upper mantle. In these terms, most of Saskat-

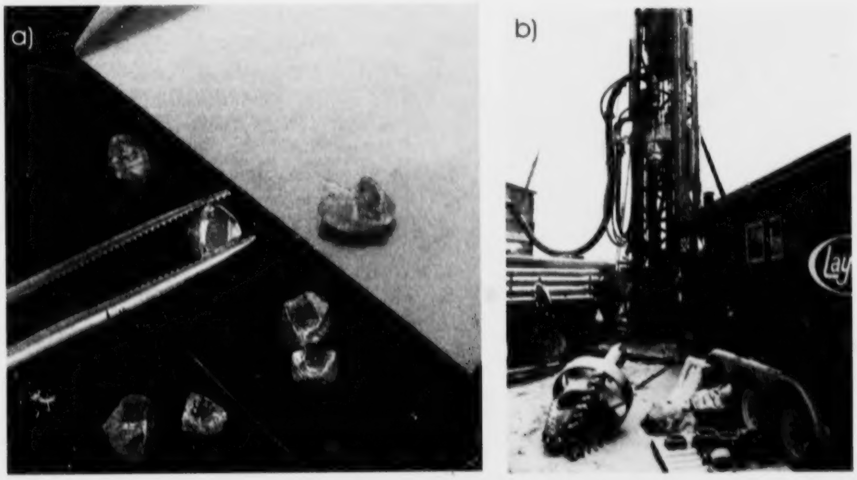


Figure 71 – a) Diamonds recovered from Fort à la Corne kimberlites (courtesy of the Fort à la Corne Joint Venture). b) Large-diameter, reverse-circulation drill rigs used for bulk sampling programs on the 140/141 kimberlites.

Table 17 – Summary of preliminary grade- and revenue-modelling forecasts for Fort à la Corne kimberlites 122 and 141.

Body	Grade forecast	Model value (SSV)	Model revenue (SSV)	Model description
	cpht (>1 mm)	US$/ct (>1 mm)	US$/tonne (>1 mm)	
122	8	133	11	***Best fit***
122	13	136	18	Optimistic
141	19	88	17	Conservative
141	19	148	28	***Best fit***
141	19	173	33	Optimistic
	cpht (>1.5 mm)	$US/ct (>1.5mm)	$US/tonne (>1.5mm)	
122	7.5	144	11	***Best fit***
122	12	147	18	Optimistic
141	18	90	16	Conservative
141	18	153	28	***Best fit***
141	18	179	32	Optimistic

chewan is considered to be favourable ground for diamond exploration. Precambrian rocks exposed on the shield in the north, and occurring at depth beneath Phanerozoic strata in the south, are interpreted as being parts of the Archean Rae-Hearne, Wyoming and Sask cratons.

Regional Quaternary indicator-mineral sampling surveys, completed by Saskatchewan Energy and Mines (Gent, 1992; Swanson and Gent, 1993), the Geological Survey of Canada (Thorleifson *et al.*, 1994; Garrett and Thorleifson, 1996) and the Saskatchewan Research Council (Simpson, 1991; Millard, 1994), revealed a number of intriguing indicator-mineral counts and geochemistries. All of these surveys have been compiled into a web-accessible database that can be fully searched. The most intriguing results are from the Val Marie and Wood Mountain–Lisieux areas of southern Saskatchewan. Many of the sample sites contain very anomalous numbers of geochemically distinct, kimberlitic indicator minerals, including high-Cr diopsides, high-Cr spinels, G10 garnets and low-Cr, high-Na garnets. The anomalies occur both in Tertiary gravels and conglomerates of the Wood Mountain Formation and in locally derived glacial tills. The source of the indicator minerals in the Wood Mountain Formation itself remains enigmatic. Kjarsgaard (1995) speculated that the source could be the Central Montana Alkaline Province, more than 300 km to the southwest. Swanson and Gent (1993) noted that many of the indicator minerals examined were coarse grained, euhedral and well preserved, and that some garnets had nonabraided, pitted, subkelyphytic surface textures. The high-energy environment required for transport of the Wood Mountain gravels does not seem compatible with such well-preserved indicator minerals, and led Swanson and Gent (1993) to postulate a more proximal source.

The compilation of all indicator-mineral geochemical surveys and numerous gravity surveys submitted to Saskatchewan Industry and Resources over the past 40 years is expected to be of value in diamond-exploration programs. The early and continued exploration successes are likely to ensure a high level of interest in diamonds in Saskatchewan for the foreseeable future.

Gold

Gold production in the province has been from placer operations on the North Saskatchewan River, and from gold and base-metal deposits in the northern Shield (Table 18). Approximately 90% of the province's gold production has been as a by-product from the Flin Flon copper-zinc mine of Hudson Bay Mining and Smelting Co. Ltd.

More than 200 gold occurrences are known and, with the exception of a few placer deposits, all are in the Precambrian Shield. The only mines to have seen significant production are the Box mine at Goldfields; the Star Lake, Jolu, Jasper and Contact Lake mines in the La Ronge Domain; and the Seabee mine in the Glennie Domain. Many other deposits, particularly in the Flin Flon–Amisk Lake region, have had limited production.

A miner named Dalton supposedly made the first gold discovery in the Shield, north of Pine Channel in 1910. A short tunnel was driven with disappointing results and, although many claims were staked in the vicinity between 1910 and 1913 and sulphide minerals were encountered, there was no further mention of gold.

The first significant gold discovery occurred three years later. Prospectors Thomas Creighton, Jack Mosher and Leon Dion, working for Toronto entrepreneur and one time prizefighter, Jack Hammell, found a gold-bearing quartz vein on the northwest shore of Amisk Lake. The prospect subsequently became the Prince Albert (Monarch) mine, named after the town in which the development capital was raised. It was mined in 1937 and again from 1940 to 1942. The discovery concentrated interest in the area and numerous other gold prospects were found, including the Graham mine and those at Robinson Creek, Waverly Island and Mosher Lake.

As with the serendipity of pitchblende discoveries in the Beaverlodge district in the late 1930s, so it was in the Amisk Lake area. In 1915, during the rush that followed the early discoveries of gold around Amisk Lake, Thomas Creighton and the Mosher and Dion brothers chanced upon a copper-zinc massive-sulphide showing that would lead to the development of the Flin Flon mine; this discovery ushered in what was soon to become a truly world class Paleoproterozoic VMS district.

In 1926, the first traces of gold were reported from the La Ronge area, in fact from the Moose Point copper showing originally identified by McInnes, as well as from the Sulphide Lake area farther north. Two years later, another significant discovery was staked at Rottenstone Lake by trappers Tremblay and Olson, likely working from information supplied by locals. This property was acquired by Richard Hall, Member of the Legislative Assembly for Cumberland, and his brother, who optioned it to Cominco. The deposit, marked by a hill of 'rotten gossanous rock', assayed high in Ni, Pt and other precious metals. It was drilled by Cominco and found to be small and uneconomic.

The 1930s to mid-1940s saw significant gold exploration, particularly in the Flin Flon area, where a number of small gold mines, notably the Henning-Maloney, Graham, Monarch and Douglas Lake (Newcor), yielded minor production. Several gold prospects were identified in the belt of metavolcanic rocks stretching northeast from La Ronge (La Ronge Belt), especially in and around Sulphide Lake. In this area, there was a small amount of production from the Preview Lake and Pap Lake prospects, and from discoveries made by a local prospector, Adolph Studer. There was considerable exploration north of Pine Channel, resulting in the discovery of several gold showings.

More significant, however, was the recognition in 1934 of gold mineralization on the north shore of Lake Athabasca, between Lodge and Neiman bays. Prospectors Tom Box and Gus Nyman made the discovery, that precipitated a major gold rush and establishment of the town of Goldfields. The Box property was optioned to Cominco, who began underground work by 1935 and, by 1937, had plans in place for mill construction. A hydroelectric plant, built at Wellington Lake, approximately 55 km to the west, supplied power for the operation. Meanwhile, two other prospects, the Athona and Frontier, which were never producers, were undergoing underground development and the town of Goldfields had grown to 1000 people. The Box mine began production in 1939 and shut down in 1942 because of the low ore grade. The town of Goldfields died with it. However, it was the serendipitous discovery of pitchblende during the heady gold rush days that would eventually give rise to one of the largest staking rushes in Canadian history, and plant the seed for the Uranium City camp.

Table 18 – Historical gold production in Saskatchewan.

Map no.[1]	Name or location	Operated	Production (troy oz.)
Placer deposits			
	North Saskatchewan River (Alberta/Saskatchewan)	1887–1909	864
	North Saskatchewan River (Saskatchewan)	1938–1943	274
	North Saskatchewan River (Saskatchewan)	1947–1949	22
Lode deposits			
Au 34	Henning Maloney and others	1933–1947	810[2]
Au 33	Prince Albert (Monarch)	1937, 1940–1942	4882
Au 2	Box	1939–1942	64,066
Au 17	Mallard Lake (Decade Mine)	1973–1975	555[2]
Au 17	Star Lake	1986–1989	76,947[3]
Au 17	Jolu (Rod Zone + Mallard)	1988–1991	203,751
Au 18	Jasper	1990–1991	82,697
Au 34	Rio	1931–1941	331
		1984	30
		1988–1989	1200[4]
Au 25	Seabee Mine	1991–present	506,106[5]
Au 21	Contact Lake	1995–1998	188,210
Au 12	Komis	1996–1997	26,885
By-product (base-metal mining)			
Cu-Zn 24	Flin Flon Mine	1930–1987	3,000,000[6]
Cu-Zn 25	Birch Lake	1957–1960	813
Cu-Zn 27	Coronation	1960–1964	75,055
Cu-Ni 6	Rottenstone	1965–1968	363
Cu-Zn 10	Anglo-Rouyn	1966–1972	67,652
Pb-Zn 6	Hanson Lake (Western Nuclear)	1967–1969	985
Cu-Zn 25	Flexar	1969–1972	7357
By-product (uranium mining)			
U 35, 36	Cluff Lake	1987–1988	7969.6

[1] refers to Mineral Resource Map of Saskatchewan, back pocket

[2] estimated

[3] includes production from 21 zone and Rush Lake zone

[4] 20,500 ton bulk sample, grading 0.12 oz./ton Au, was mined; intention was to process in two halves (10,000 and 10,500 tons); processing of first 10,000 tons completed August 1988; grades were apparently too low for company to proceed with second half, although this intention is stated in a news article that refers to Vista having custom-milled ore from the Cameco-Husky test mine at Laural Lake before proceeding to mill the balance of the Rio ore

[5] production to June 2001

[6] for entire deposit (Saskatchewan and Manitoba)

The postwar years proved to be a period in which base-metal exploration and development thrived, whereas gold activity faltered, largely because of the fixed gold price of US$35 per ounce. Irrespective of this, several important gold discoveries were made, mainly in the La Ronge Belt and particularly by prospector Eric Partridge and prospectors working for Cominco, who remained active after closure of the Box mine. Partridge's discoveries included the Kaslo near Tower Lake (1958), the Komis at Waddy Lake (1958), and the Kahn veins at Star Lake (1961), whereas Cominco prospectors found Weedy Lake (1948) and the Seabee zone at Laonil Lake (1949). Although these and other previously discovered prospects were examined by trenching and some drilling, it was not until the 1980s that they would be subjected to intensive exploration.

Gold exploration remained stagnant during the 1970s, with only one short-lived attempt at gold production by Decade Development Ltd., between 1974 and 1976 at the Mallard Lake mine, 120 km northeast of La Ronge. The prospect, named the Jolu, had been discovered and drilled by Cominco in 1944. Although the operation did not prove to be profitable, the mill was maintained and, some 20 years later, served to focus interest on the area.

Revitalization of exploration occurred with the surge in gold prices of 1975-1980, and expenditures followed a nationwide upward trend (Figure 41). Thus, although the price of gold declined from the peak of 1980, the gold exploration boom continued, fuelled by low prices for other commodities and, in Canada in particular, by a favourable investment climate created by 'flow-through financing'. This exploration phase led primarily to re-examination and upgrading of historically known showings, mostly in the La Ronge Belt but also around Flin Flon and in the Glennie Domain. New deposits found during this period included the Star Lake 21, Rod (Jolu), Jasper and Bakos (Contact Lake), all of which would become mines, as well as many new showings. The mid- to late 1980s also saw gold discovered in the far northeastern part of the province, in Archean Ennadai Group volcanics near Hatle Lake. In 1987, Claude Resources Inc. made an interesting gold discovery in upper amphibolite to granulite facies metavolcanic rocks with associated iron formations in the Ithingo Lake area of the Mudjatik Domain. This discovery showed that the largely ignored terrains of high metamorphic grade, such as the Mudjatik Domain, contain possible exploration targets.

In 1987, the Saskatchewan Mining Development Corporation (now Cameco Corporation) brought the first of the new deposits, the Star Lake 21 zone, discovered in 1983, into production. It was mined out, together with the nearby small Rush zone, by mid-1989 after producing 2 393 kg (76,947 oz.) of gold. The Jolu (Rod) mine, operated by Corona Corporation, followed in November 1988 and was mined out by mid-1991, with production of 6 337 kg (203,751 oz.) of gold, part of which was from the historic Mallard Lake zone.

The Jasper or Fork Lakes mine, operated by Cameco, began operations in April 1990; mining was completed in May 1991 and milling in December 1991. Ore was processed at the Star Lake mill and 2 572 kg (82,697 oz.) of gold were produced.

Claude Resources Inc., a junior mining company based in Saskatoon, succeeded in bringing the Seabee deposit to production in November 1991. The deposit is located to the east of the La Ronge Belt, at Laonil Lake, about 120 km northeast of La Ronge. A second shaft was added in 1997. Discovery and definition of new reserves has kept pace with mining, and annual production continues to top 1 500 kg (50,000 oz.) of gold. The 500,000 oz. production milestone was passed in the second quarter of 2001, and the Seabee mine has become Saskatchewan's largest primary gold producer.

The Contact Lake mine, jointly owned by Cameco and Uranerz Exploration and Mining Ltd., and located 40 km north of La Ronge, close to Highway 102 in the La Ronge Provincial Park, commenced production in January 1995. With initial mineable reserves of 1.3 million t grading 8.0 g/t (0.23 oz./ton) Au, this deposit was significantly larger than any deposit found previously in the La Ronge Belt. Reassessment based on underground exploration and development, however, downgraded reserves and resources by the end of 1995. No additional reserves were discovered, and the mine ceased operation in 1998 after producing 5 206 kg (167,385 oz.) of gold.

The Komis deposit, discovered in 1958 by E. Partridge and located 145 km northeast of La Ronge, was brought into production by Waddy Lake Resources Inc. in August 1996. Ore was hauled about 80 km by road for processing at the Jolu mill. Mining was short lived, however, because a combination of haulage costs, lower than expected mill-head grades, recovery problems, dilution factors, and a low gold price made mining uneconomic. Operations ceased in January 1997.

In the Flin Flon area, the Rio deposit, originally discovered in 1936, has been the subject of two short-lived attempts at commercial production, in 1984 and 1988 to 1989. The nearby Laural Lake gold-silver deposit, on Missi Island in Amisk Lake, has also been evaluated underground and was deemed by the operator at the time, Cameco, to be uneconomic at current gold prices. In 1995, Claude Resources Inc. optioned the Laural deposit and, by the end of 1999, had earned a 35% working interest in the property. Claude estimates the deposit resource for Laural to be 1 423 065 t (1,568,218 tons) grading 13.4 g/t (0.39 oz./ton) Au over a mineable width, but further exploration has been deferred until gold prices improve.

Although recent exploration interest has focused on the La Ronge Belt, gold exploration throughout the past decade has constituted, at most, 28% (1995) of the total annual exploration expenditures for the province, and only 9% in 2002 (Figure 41).

General Geology

Gold mineralization is found mainly in the Early Proterozoic volcanoplutonic regimes of the La Ronge and Flin Flon domains (*Mineral Resource Map of Saskatch-*

ewan, back pocket), and in the intervening Glennie Domain. Several occurrences are also known in the Mudjatik Domain and in the Goldfields (e.g., Box mine) and Pine Channel areas north of Lake Athabasca. Gold mineralization in the La Ronge Domain is mostly structurally controlled and of quartz-vein type. Host rocks, in addition to metavolcanics and metasediments, are predominantly plutons of varied composition. Controlling structures may be high-temperature shear zones that are essentially contemporaneous with the main thermotectonic events (Star Lake 21, Rod, Jasper, Pap and Bakos zones, and the Seabee deposit in the Glennie Domain), or later(?), low-temperature, retrograde, regional fault structures such as the Byers Fault (Tower East and Weedy B–Golden Heart zones). The Komis deposit at Waddy Lake, where swarms of north-striking quartz veins cut meta-andesites flanking a late-tectonic diapiric granodiorite-granite stock, illustrates another style of structurally controlled mineralization.

Gold also occurs in clastic rocks: associated with disseminated sulphides (Greywacke zone) in the former MacClean Lake Belt and within quartz-vein systems (North Lake zone) in the McLennan Group. The latter style of mineralization appears to be pretectonic, epigenetic and possibly epithermal in character; it has been suggested that the former type is of reworked placer origin.

Stratiform gold occurrences are most extensive in the Sulphide Lake area, where gold is closely related to the presence of black, carbonaceous, sulphidic meta-argillite layers (lean iron formation), developed during hiatuses in intermediate-felsic volcanism and sedimentation.

The Flin Flon–Amisk Lake area features a spectrum of pre- and syn- to late-tectonic mineralization. Early-generation gold occurrences (Monarch mine, Graham mine, Laural Lake deposit) in the West Channel area of Amisk Lake are quartz-vein systems, surrounded by alteration haloes of carbonate, sericite and silica, that are developed in metavolcanics, interlayered metasediments and felsic intrusives in both subvolcanic and structural settings. Formation in a near-surface, possibly epithermal environment is suggested. By contrast, the Flin Flon area is characterized by structurally controlled deposits in metavolcanics and invading plutons. Early quartz-sulphide-gold veins were emplaced in intermittently active fractures during orogenesis (Newcor mine), whereas later, predominantly plutonic-hosted deposits (Rio, Phantom Lake mine, Henning-Maloney mine), were likely generated by an anorogenic porphyry system.

The Pine Channel area, north of Lake Athabasca, is typified by gold-bearing quartz veins occupying northwest-trending dilational fractures. Host rocks are retrogressed, Archean, granulite-facies, garnetiferous quartzofeldspathic gneisses and hypersthene-bearing metabasic rocks (norites). Gold was presumably derived from the country rocks by retrogressive metamorphic fluids.

At Goldfields, gold mineralization is hosted in discrete Early Proterozoic granitic bodies of magmatic and metasomatic origin, cut by quartz-vein stockworks. The quartz-vein stockworks are structurally controlled and developed during a late-tectonic event, which was accompanied by retrograde metamorphism marked by regional chloritization and, in the Box and Athona granites, by albitization.

Lode Gold Deposits

Box Mine (Figure 72)

Geology: The Box mine is located south and east of Uranium City. The deposit is contained within a sill-like body of pyritic peraluminous granite, cut by a stockwork of gold-bearing quartz veins. It is 800 m long, 37 m in average width, dips moderately to the southeast, and is enclosed by overlying foliated granite and underlying quartzite. The quartz veins include sulphides and gold, together with albite, tourmaline and chlorite. The veins vary from microscopic dilational gashes to planar bodies several centimetres in width and traceable over many metres. They are typically closely confined within the host granite. Wall-rock alteration is not apparent adjacent to veins, although retrograde chlorite-grade metamorphism apparently accompanied vein formation. Gold, typically associated with pyrite, sphalerite and chalcopyrite, occurs primarily in the quartz veins but also in the wallrock. It is found free in pyrite and as coatings on microfractures.

History and Production: The Box deposit was staked in 1934 and, within a year, underwent development by The Consolidated Mining and Smelting Co. of Canada Ltd. (later Cominco Ltd.). Two inclined shafts were

Figure 72 – Historic Box mine complex, Beaverlodge district. The mine was in operation from 1939 to 1942.

sunk, the No. 1 in the footwall toward the west end of the orebody for exploration and the No. 2, a three-compartment shaft, at the east end of the orebody for production. Levels were established at 30 m (100 ft), 91 m (300 ft) and 152 m (500 ft), and drifts were driven along the footwall contact. Difficulties in estimating grade became apparent early in development, because, although the host rock carried low gold values, potential ore required the presence of crosscutting quartz veins that contained elevated but erratic gold values.

Following initial stope development in mid-1938, mined grade proved significantly lower than reserve grade and additional underground drilling was undertaken. The new reserve figures, although much reduced in grade from 4.8 g/t (0.14 oz./ton) to less than 2.4 g/t (0.07 oz./ton), still provided sufficient encouragement to uphold the production decision and a 1000 t/day mill began operation in June 1939. The first gold brick was poured on August 15 of that year. Between 1939 and 1942, the mine produced 1 868 kg (64,066 oz.) of gold from ore grading 1.55 g/t (0.0452 oz./ton) Au, at a cost of $30-40 per ounce.

Contact Lake Mine

Geology: The Bakos structure is a poorly exposed, regional, pyritized, sericitized and hematized shear cutting the Little Deer Lake Pluton. Gold mineralization was in millimetre- to centimetre-scale quartz veins and sulphide veinlets and disseminations in the altered hanging wall of the shear zone. Sulphide minerals were predominant pyrite, lesser amounts of chalcopyrite and pyrrhotite, and minor galena, sphalerite, molybdenite, bornite, marcasite, chalcocite and native bismuth. Visible gold was relatively common. In the main part of the orebody (the BK-1 and BK-2 zones), 86% of the gold occurred in silicates, 10% in pyrite and 4% in carbonate and carbonate-silicate aggregates; in contrast, the gold in the BK-3 zone was mostly sulphide hosted.

History and Production: The claims were staked for Saskatchewan Mining Development Corporation (now Cameco Corporation) in 1979 over an area then known to contain several minor gold occurrences. Extensive geological, geophysical and geochemical surveys of the area culminated in 1987 with the discovery of the mineralization by bulk till sampling and heavy-mineral separation. Follow-up ground HLEM and magnetic surveys and diamond-drilling were followed by a two-stage, 11 800 m diamond-drill program in 1988 to fully delineate the Bakos zones, BK-1 and -2. Cameco (50%; as operator) and partners Uranerz Exploration and Mining Ltd. (30%) and Westward Exploration (20%) were by 1990 able to report an initial estimate of mineable reserves in the BK-1 and -2 zones of 1 322 400 t grading 8.2 g/t (0.24 oz./ton) Au (equivalent to 10 522 kg [338,310 oz.] of gold) to 250 m. Bakos 3 possible reserves were reported as 250 000 t grading 12 g/t (0.35 oz./ton) Au (equivalent to 3 000 kg [96,000 oz.] of gold).

Exploration resumed in 1992 with a 51-hole 12 800 m diamond-drilling program that was completed by mid-April. In the BK-3 zone, 34 holes confirmed the continuity and grade indicated by earlier widely spaced holes. Possible reserves for BK-3 were redefined to 227 000 t grading 12 g/t (0.35 oz./ton) Au. A 5.5 km access road was completed in October 1993, and the decline collared and driven to a depth of 100 m. The feasibility study identified 1 313 000 t grading 8.01 g/t (0.23 oz./ton) Au, for an estimated production of 10 500 kg (338,000 oz.) of gold. A 10-hole 5000 m diamond-drilling program to 460 m below surface to test the down-plunge extension of the orebody showed below-average grades and multiple intersections, except for the final hole drilled down-plunge of the main ore zone. This returned several sections of above-average grades, including 9.23 g/t (0.269 oz./ton) Au over 3 m and 19.07 g/t (0.556 oz./ton) Au over 2.5 m.

Construction work started in April 1994, with development on four levels from the decline to the 5290 (160 m) level completed by September and the 700 t/day mill ready by December. Mining started January 1995, the official opening being February 22. The mine was jointly owned by Cameco (66.67%; as operator) and Uranerz Exploration and Mining Ltd. (33.33%). End-of-year reserves were estimated as equivalent to 4 600 kg (149,000 oz.) of gold, and gold equivalent in reserves and resources was recalculated downward from 18 600 kg (600,000 oz.) to 13 400 kg (432,000 oz.).

In 1996, the 850 t/day mill processed 268 964 t ore at a mill-head grade averaging 6.20 g/t (0.18 oz./ton) Au, with a recovery of 92.96%, to produce 1 475 kg (47,434 oz.) of gold. The Bakos zones reserve total on December 31 was 455 000 t grading 7.2 g/t (0.21 oz./ton) Au for a total of 3 280 kg (106,000 oz.) of gold, and total resources were estimated at 392,000 t grading 7.5 g/t (0.22 oz./ton) Au, for a total of 2 900 kg (94,000 oz.) of gold. However, lower than expected ore grades reaching the mill reduced production levels and raised costs, and further underground exploration drilling failed to replenish reserves.

In 1997, 292 722 t of ore, mined at a mill-head grade of 6 g/t (0.17 oz./ton) Au, produced 1 756 kg (52,593 oz.) of gold. The remaining reserves of 182 000 t grading 6.5 g/t (0.2 oz./ton) Au (equivalent to 1 180 kg (38,000 oz.) of gold) were depleted and the mine ceased operations in early June 1998.

Jasper Mine

Geology: The Jasper mine was located in the La Ronge Greenstone Belt, 135 km north of La Ronge and 4 km south of the Star Lake mine. The Jasper gold deposit was structurally controlled within a northeast-trending shear zone in the granite-granodiorite Island Lake Pluton. The shear zone is steeply dipping, exhibits an anastomosing horsetail-like configuration and hosts several ore shoots with steep northerly plunges.

The Jasper-James and Muskeg zones occupied the main structure, whereas the Roxy zone to the north occurred in a north-northeast-trending splay. Gold and accompanying sulphide mineralization were hosted by sheared mylonitized granite and early 'cherty' quartz veins, and by later massive quartz veins. The gold in the mineralized zones generally occurred in silicate aggregates, although it was also present within pyrite. Pyrite was the dominant sulphide and was accompanied by accessory marcasite, galena, sphalerite and chalcopyrite, and traces of tetrahedrite, covellite, bornite and pyrrhotite. Adjacent to auriferous zones and within the shear zones generally, alteration was marked by muscovite, sericite, chlorite and tourmaline. Hanging-wall and footwall rocks comprise undeformed massive granite, commonly in sharp contact with the mineralized shear zones.

History and Production: The Jasper mine was discovered in June 1987 on the Fork Lakes property of Cameco Corporation (36%), Golden Rule Resources Ltd. (30%), International Mahogany Corporation (19%) and Shore Gold Fund (15%). The discovery was made during a systematic mapping and prospecting program focused on the Island Lake Pluton, which had been identified as geologically similar to the nearby Star Lake Pluton, the host to the Star Lake 21 zone and Jolu deposits. Diamond-drilling of 23 holes (2680 m) in 1987 and a further 63 holes (13 700 m) in 1988 was undertaken to prove up ore reserves in the Jasper discovery zone and adjacent mineralized structures (Roxy and Muskeg zones). At the same time, exploration was ongoing on the adjacent Transom Lake property to the south, which contained a mineralized extension of the Jasper structure, referred to as the James zone.

Underground exploration was initiated in July 1988 to prove up mineable reserves in the combined Jasper-James orebody, with the sinking of a 150 m deep decline and development on the 45, 90 and 150 m levels. A production decision was made in December of 1988; however, disagreement among the joint-venture partners regarding a production plan caused operations to be suspended through 1989. A change of ownership to Cameco (80%) and Shore Gold Fund (20%) was negotiated for both the Fork Lake and Transom Lake properties in late 1989, allowing production to begin in April 1990. Mineable reserves at this time were estimated at 163 000 t grading 16.1 g/t (0.47 oz./ton) Au, indicating total production at 2 600 kg (85 000 oz.) of gold and a mine life at two years, with ore processing to be carried out at the nearby, refurbished, 230 t/day Star Lake mill. The last ore was mined on May 10, 1991 and hauled to surface on May 25, 1991. Milling was completed by mid-December 1991. Total production was 2 634 kg (82 697 oz.) of gold from 140 127 t of ore at a mill-head grade of 18.8 g/t (0.55 oz./ton) gold and a recovery rate of 97%.

Jolu Mine

Geology: The Jolu or Mallard Lake property is located in the Star Lake area of the La Ronge Domain, 3 km north of the Star Lake 21 zone. The geological setting at the Jolu mine is similar to that of the adjacent 21 zone. The composite Star Lake Pluton, which ranges in composition from granite in the core to diorite at the margin, intrudes Early Proterozoic mafic to felsic volcanic flows and pyroclastics and interlayered sediments (biotite schists), metamorphosed to lower amphibolite facies grade.

Gold-quartz mineralization in both the Rod Main and Mallard Lake zones was structurally controlled within shear zones trending 060° and marked by mylonites, particularly apparent in the Star Lake Pluton. Intersection with a more northerly-trending (035°) fracture system was possibly significant. The plunge of the gold-quartz mineralization varied from 30°SW in the Rod Main zone to 12°SW in the Mallard zone. These compare with a plunge of 60°SW for the Star Lake 21 zone mineralization, which was located in a similar northeast-trending shear zone in the Star Lake Pluton. The Rod South and Lake veins at Mallard Lake are gold-quartz vein fillings of tension gashes that trend 080°.

The gold-quartz mineralization in these zones was characterized by pyrrhotite, pyrite and chalcopyrite. Visible gold was common and usually associated with molybdenite. There was also significant tourmaline at Mallard Lake. Gold values tended to be erratic, in part due to the coarseness of the gold; however, the tension-fracture style of mineralization appeared more consistent and of higher grade. There was no significant alteration halo apparent around the zones of mineralization.

History and Production: Cominco Ltd. acquired the property in 1944, discovered the Mallard Lake gold deposit by prospecting and identified, through drilling, about 23 000 t of ore grading approximately 20.6 g/t (0.6 oz./ton) Au. Decade Development optioned the property in 1972 and attempted commercial production, extracting a small amount of gold from underground between 1973 and 1976. Mahogany Minerals Resources Inc. acquired the property in 1982; however, no significant exploration was undertaken until 1984, when Goldsil Resources Ltd. obtained control of Mahogany. An exploration program confirmed and increased reserves in the Mallard Lake zone and, more importantly, led to discovery of the new Rod Main and Rod South zones of mineralization.

Royex Gold Mining Corporation developed an interest in the property in 1985, initially by providing exploration funding in return for shares in Canadian Premium Resources Corporation, which had acquired an option to earn a 50% interest in Jolu in June 1985. In 1987, through restructured agreements, Royex became operator of the property with a 30% direct interest. Royex amalgamated with International Corona Resources Ltd., Lacana Mining Corp., Mascot Gold Mines Ltd. and Galveston Resources Ltd. to become Corona Corporation on July 1, 1988. Underground development was initiated in 1987 and a decline driven to the 170 m level and then to the 290 m level to prove up reserves quoted at 606 000 t grading 13.7 g/t (0.4 oz./ton) Au in the Rod zone and 18 350 t grading 22.7 g/t (0.66 oz./ton) Au in the Mallard Lake zone. The $18.3 million, 400 t/day mine-mill complex began production with the pouring of a 35.1 kg (1130 oz.) gold brick on November 15, 1988. The last ore was mined in December of 1990, the last ore was hauled from underground in May 1991, and milling was completed on August 12, 1991. Total production was 6 800 kg (203,751 oz.) of gold from 472 220 t of ore at a mill-head grade of 14.4 g/t (0.42 oz./ton) Au, representing a gold recovery rate of around 97% and an average cost of US$143 per ounce.

Star Lake Mine

Geology: The Star Lake mine is in the centre of the La Ronge Belt (*Mineral Resource Map of Saskatchewan*, back pocket). The orebody is structurally controlled and occurs close to the footwall of a shear zone where mylonites are developed. The structural zone dips steeply to the northwest, is approximately 50 m wide in the vicinity of the mine, and occurs in variably deformed quartz monzonite that exhibits both planar and linear tectonite fabrics. The lineation on shear surfaces plunges steeply to the southwest. The orebody consisted of massive quartz veins containing disseminated pyrite and gold. It had a strike length of 80 m, depth extension of 180 m and maximum width of 14 m, and plunged to the southwest at approximately 60°. There was no visible wallrock alteration associated with the mineralization. Free gold occurred as very fine grains included in broadly equal quantities of quartz and pyrite.

The 21 zone orebody was within a northeast-trending structural zone in the composite Star Lake Pluton. This pluton ranges in composition from dioritic at the margins to granitic in the core. Mafic dykes and inclusions of the surrounding, predominantly basic to intermediate metavolcanics are characteristic of the quartz monzonitic phase that hosted the orebody. The Kahn 18 zone was in an adjacent, parallel structural zone but was of different style, marked by intensely sheared 'ribboned' rather than massive 'late' quartz. Milled and attenuated sulphide grains were also characteristic of this zone.

Gold occurrences in the Star Lake area also appear closely related to the Star Lake Pluton and are found at the contact with the country rocks (e.g., Mallard Lake and Tamar occurrences) or within the pluton (e.g., Rod, Rush (Pie), 21, Kahn 18 and Blindman zones). In many of these, there is a clear association with northeast-trending structural zones.

History and Production: The Star Lake mine (21 zone) was owned jointly by Cameco Corporation (50%), Starrex Mining Corporation (35%) and Uranerz Exploration and Mining Ltd. (15%). The history of the area, 135 km northeast of La Ronge and 10 km west of Highway 102, dates to 1961 when prospector Eric Partridge staked the Kahn claims over quartz veins from which he had panned gold. Two veins, named the Kahn 18 and 28, were trenched and one hole drilled on the 18 vein. Also in 1961, M. and E. Hird staked claims to cover an adjacent zone of mineralization, the Rush (Pie) zone. In 1981, the property was acquired by a Saskatchewan Mining Development Corporation–Phoenix Canada Oil Co. Ltd. (later Starrex Mining Corporation Ltd.) joint venture, and exploratory drilling was carried out on the 18 vein. Follow-up drilling in 1983 led to discovery of the adjacent 21 zone. Reserves in 1984 totalled 208 650 t grading 17.1 g/t (0.5 oz./ton) Au at a cut-off grade of 3.4 g/t (0.1 oz./ton) to a depth of 130 m. An additional 17 000 t of reserves grading 10.2 g/t (0.32 oz./ton) Au were identified in the Rush zone.

Development of the 21 zone began in late 1985 with the sinking of a decline. Mining was by the blasthole open-stope method, supplemented by shrinkage stoping. Start-up of the 200 t/day mill took place in late 1986 and the first test gold bar was poured on January 2, 1987. Production was 1 030 kg (33,126 oz.) of gold in 1987, 1 047 kg (33,688 oz.) in 1988 and 315 kg (10,133 oz.) in 1989. Mining was completed in late 1988, feed for the mill for the first quarter of 1989 being provided by the nearby Rush zone. Total production was 2 650 kg (76,947 oz.) gold from 180 291 t of ore at a mill-head grade of 14.7 g/t (0.43 oz./ton) Au, a recovery rate of approximately 93% and an average cost of around US$175 per ounce. An estimated 10 000 t of ore grading 8.2 g/t (0.24 oz./ton) was left unmined.

Seabee Mine (Figure 73)

Geology: The Seabee deposit is located on the prominent peninsula at the northeast end of Laonil Lake, in the Glennie Domain. The deposit is structurally controlled in a near-vertical ductile shear zone cutting medium- to coarse-grained leucocratic to melanocratic metagabbro of the Laonil Lake Intrusive Complex. In the vicinity of the veins, this complex comprises a series of gabbroic layers or sheets cut and commonly capped by quartz diorite. Ultramafic layers or lenses lie at the base of some sheets. Intercalated or rafted within the intrusive are variably thick layers, lenses and xenoliths of mafic metavolcanic rocks and less common metagreywacke. The complex is cut by ultramafic and intermediate dykes. This entire assemblage is metamorphosed to amphibolite-facies grade.

Ore is hosted in discontinuous quartz-tourmaline veins confined to a series of east-northeast-trending, near-vertical shear zones. The veins are isoclinally folded about axes that plunge steeply west-southwest, parallel to a penetrative mineral lineation. Individual shears are up to 200 m long. Narrow, sulphide-bearing, feldspar-porphyry bodies, within and adjacent to the shear zones, appear to be genetically associated with the quartz veins. The shear zones are thought to be contemporaneous with the major Laonil Lake Shear Zone, which forms the southern contact of the Laonil Lake Intrusive Complex with the diapirically emplaced Eyahpaise Lake Pluton. Ore zones are 1.8 to 5 m thick. Gold mineralization occurs in sulphide grains and quartz veins, as visible gold and gold-bearing pyrite, chalcopyrite and pyrrhotite. Other minerals in the veins include tourmaline, tellurides, magnetite, actinolite-tremolite, sericite, sphalerite, molybdenite and barite. In and adjacent to the shear zones, there is a pervasive potassic alteration halo marked by the appearance of biotite in place of hornblende. Sulphidization and irregular carbonatization have also been documented.

History and Production: Seabee was staked in 1949 by Cominco. Over the next 35 years, Cominco drilled 117 holes and dug several trenches to evaluate the gold content of the mineralized veins. Claude Resources purchased the property in 1984, completed some additional drilling and carried out an ore-reserves study. In 1985, Placer Development Ltd. entered into an agreement with Claude to gain a 55% interest in the property. By early 1987, Placer had completed 72 additional diamond-drill holes, as well as extensive overburden stripping, detailed sampling and remapping of the property. Later in 1987, Placer completed an underground exploration program that included 900 m of underground development, bulk sampling and 6200 m of underground drilling. In 1988, Placer terminated its joint-venture agreement with Claude. In late 1988, Claude commissioned ACA Howe International Ltd. to complete an ore-reserves study. This investigation concluded that the main zone, comprising veins 2 and 5, contained proven and probable ore reserves of 585 135 t grading 12.5 g/t (0.36 oz./ton) Au and possible ore reserves of 332 937 t grading 12.5 g/t (0.36 oz./ton) Au. In late 1989, Claude engaged Cominco Engineering Services Ltd. (CESL) to manage a $2 million program that included 3960 m of diamond-drilling, an additional 300 m of underground development and bulk sampling. On May 15, 1990, based on the final feasibility study by CESL that reported reserves (all classes) of 1.03 million t grading 13.7 g/t (0.4 oz./ton) Au, Claude decided to proceed with production. Mine development, construction of a 400 t/day mill and construction of a 60 km winter road from Brabant Lake were initiated in 1991. First production was achieved in November 1991.

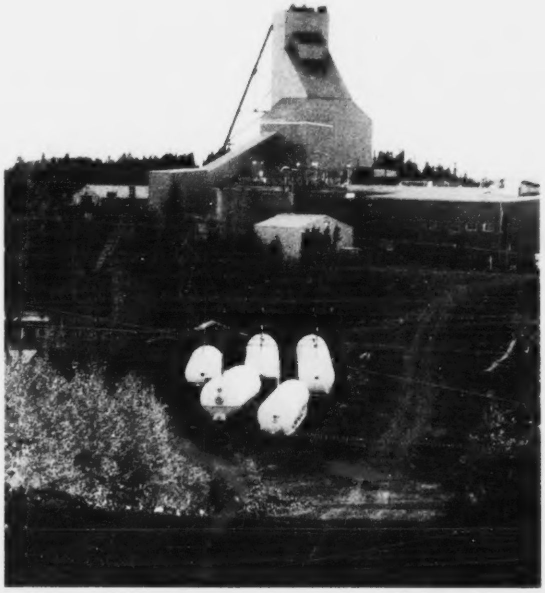


Figure 73 – Seabee mine headframe at Laonil Lake in east-central Saskatchewan (courtesy of Claude Resources Inc.).

At this time, proven, possible and probable reserves were estimated to be 1 036 000 t grading 13.7 g/t (0.4 oz./ton) Au; inferred reserves were estimated to be 907 000 t grading >10.3 g/t (>0.3 oz./ton) Au. From January to April 1992, 13 700 m of surface and underground diamond-drilling resulted in a downward revision of reserves. Remaining recoverable diluted reserves in the 2B and 5-1 zones (including stockpiled ore) were quoted as 107 000 t grading 11.8 g/t (0.34 oz./ton) Au. Total production for 1992 was 1 438 kg (58,664 oz.) Au from 167 515 t ore, at an average mill-head grade of 11.57 g/t (0.34 oz./ton) Au and a milling rate of 458 t/day. Zone 5 provided 20 000 t ore and zone 2 provided 148 000 t. A new decline was put down 45 m into the 5-1 zone, where mining began in September 1992.

In June 1995, Seabee became Saskatchewan's largest-ever primary gold producer (Tables 18, 19). Work continued on development of the 162, 163 and 75 zones, and mining continued in the 2, 5 and 161 zones. The shaft reached 395 m in depth, and the fully automated hoist and headframe were completed and became operational on October 1, 1997 at a cost of $3.5 million.

The mill rate was increased to 700 t/day and mining of new gold zones to the west, southwest and east of the 2 zone mine portal commenced. In mid-May 1998, drifts reached into the 2C structure at the 110, 190 and 290 m levels on the adjacent Currie Rose property, and development of the Currie Rose deposit west of the Seabee boundary, between the 110 and 290 m levels, started the following year. By 2000, the 2C crown pillar was mined out and production was from the Currie Rose 2D massive-sulphide zone. A program of 37 diamond-drill holes, totalling 5397 m, on the Currie Rose claims confirmed weak to modest gold values in shear-hosted quartz veins in the Laonil Lake shear corridor west of the mine. In the second quarter of 2001, Seabee achieved the milestone of having produced 500,000 oz. of gold.

Placer Gold

Placer-gold production from the North Saskatchewan River is poorly documented. Gold has been gleaned from between Rocky Mountain House, Alberta and Prince Albert, Saskatchewan. Most mining has been small scale and involved working of river-bank gravels in grizzlies and recovering the fine flour gold on blankets, although dredges were operated between 1887 and 1909 (Figure 74). In 1904 to 1905, for example, a steam-powered dredge, 30 m long, 8.5 m wide and capable of working 1000 m^3 of gravel per day, was assembled in Prince Albert and worked at Crutwell, 32 km upstream, until 1909. Two other rivers north of the North Saskatchewan, the Waterhen and Poplar rivers, were examined for their placer potential, apparently without success.

Resources and Current Production

Historical gold production in Saskatchewan has come from four principal sources (Table 18): placer deposits, lode deposits, as a by-product from base-metal mining, and as a by-product from uranium mining. Of these, base-metal mines are by far the most important source: more gold has been produced from the giant, Proterozoic Flin Flon VMS deposit than from all other Saskatchewan sources combined.

In 2002, the Seabee mine was the sole primary gold producer in Saskatchewan, with additional production from the Box mine targeted for 2003 and potential future reserves in numerous exploration properties (Table 19). Seabee, owned by Claude Resources Inc., has produced, from the start of underground operations in 1991 to the end of 2001, 2.1 million t of ore and surpassed 500,000 oz. of gold. For the year ending December 31, 2001, 275 000 t of ore were mined, at an average grade of 6.13 g/t (0.179 oz./ton) Au, compared to 8.58 g/t (0.25 oz./ton) Au in 2000. Reserves at the beginning of 2002, including proven, probable and inferred categories, were 1.6 million t grading 7.9 g/t (0.245 oz./ton) Au.

The Box mine property was re-evaluated by a consortium of companies from the Kasner Group in 1987-1989, through an extensive drilling and surface bulk-sampling program. In 1990, new geological reserves of 22 673 000 t grading 1.85 g/t (0.054 oz./ton) Au were announced for a potential 265 m deep open pit on the site of Box mine. A revised estimate, done in 1995 as part of a bankable feasibility study, gave combined mining reserves, cut to 17 g/t (0.5 oz./ton) and using a cut-off grade of 0.5 g/t (0.05 oz./ton), of 16 572 000 t grading 1.7 g/t (0.05 oz./ton) Au, equivalent to 28 170 kg (890,000 oz.) of gold. A 1997 due-diligence assessment of ore reserves, by Behre Dolbear and Co. Ltd., gave an *in situ* all-category resource of 10 494 448 t grading 2.2 g/t (0.064 oz./ton) Au, compared to the Greater Lenora Resources Corporation estimate of 12 068 615 t grading 1.9 g/t (0.055 oz./ton), equivalent to 22 900 kg (737,234 oz.) of gold. The Goldfields Operating Co. was formed in 1999 by an equal-share joint-venture partnership between Greater Lenora Resources Corporation, Cantera Mining Ltd. and Tomin Resources Ltd., and an announcement was made that small-scale development and production would proceed. On July 10, 2000, an agreement was reached with Can Am Construction of La Ronge to construct and operate the Box mine. Metallurgical tests completed by Gekko of Australia in February 2001 indicated that suitable gold recoveries could be achieved by gravity separation alone. In May of 2002, GLR Resources tabled conditional approval for production at the Box mine, given a gold price of greater than $300 and annual production of 1 200 kg (40,000 oz.) of gold averaged over a minimum of ten-year mine life. The announcement was based on a reserve estimate of 9.8 million t grading 2.16 g/t (0.06 oz./ton) Au for the Box mine and 1.7 million t grading 2.32 g/t (0.068 oz./ton) Au for the Athona mine.

Magnesium

Large resources of carnallite are associated with the four potash-bearing members of the Devonian Prairie

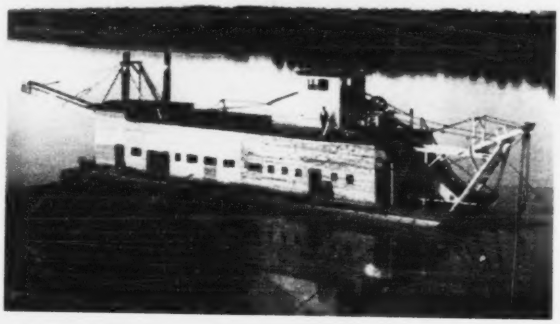


Figure 74 – Large dredge on the North Saskatchewan River, 1905 (courtesy of Saskatchewan Archives Board, Photo No. R-A 5761).

Table 19 – Published reserves and resources, nonstandardized, for selected gold deposits and exploration properties in Saskatchewan.

Map no.[1]	Ownership[2]	Share (%)	Mine or deposit	Reserves (t)	Production (oz. gold)	Gold grade	
						g/t	oz./ton
Mined out or to date							
Au 17	Cameco Corporation	50	Star Lake mine		76,947		
	Starrex Minng Corporation Ltd.	35	21 & Rush zones[3]	182 291		14.7	0.43
	Uranerz Exploration and Mining Ltd.	15					
Au 18	Cameco Corporation	80	Jasper mine[3]		82,697		
	Shore Gold Inc.	20		140 127		18.8	0.55
Au 17	Corona Corporation	30	Jolu mine		203,751		
	International Mahogany Corporation	70	Rod & Mallard[3]	472 220		14.4	0.42
Au 25	Claude Resources Inc.	100	Seabee		506,106[5]		
				1 034 200[4]		13.7	0.40
Au 21	Cameco Corporation	100	Contact Lake mine		188,210[7]		
			Bakos zones[3]	1 304 000[6]		8.00	0.23
Au 12	Golden Rule Resources Ltd.	100	Komis		268,856		
Reserves							
Au 25	Claude Resources Inc.	100	Seabee mine	579 349[8]		7.54	0.22
Au 3.2	Greater Lenora Resources Corp.	100	Box & Athona mines	12 070 000		1.9	0.055
Au 10	Kristo Gold Inc.	100	Anglo-Rouyn mine	1 180 000[9]		0.55	0.016
Au 12	Waddy Lake Resources Inc.	100	Komis & EP deposits	687 300[10]		10.3	0.30
				573 300[11]		13.4	0.39
Resources							
Au 13	Cameco Corporation	55	Corner Lake	181 500		13.0	0.38
	Golden Rule Resources Ltd.	45					
Au 21	Cameco Corporation	100	Contact Lake				
			(Bakos zone)	92 000		7.5	0.22
Au 22	Cameco Corporation	100	Pap SW	233 000		8.0	0.23
Au 25	Claude Resources Inc.	100	Seabee	1 680 000[8]		8.0	0.23
Au 33	Claude Resources Inc.	35	Laural Lake	210 000		15.0	0.44
	Cameco Corporation	32.5					
	Husky Oil	32.5					
Au 15	Golden Rule Resources Ltd.	100	Niko (Kaslo)	164 700		4.8	0.14
Au 14	Golden Rule Resources Ltd.	100	Tower East	922 000		6.9	0.20
Au 19	Masuparia Gold Corporation	100	Greywacke	297 555[12]		9.26	0.27
Au 20	Radcliffe Resources Inc.	100	'North' Lake	2 360 000		2.4	0.07
Au 10	Petro Plus Inc.	100	Twin	351 000		6.2	0.18
Au 11	Tyler Resources Inc.	50.1	Weedy B	314 000		4.8	0.14
	Golden Rule Resources Ltd.	37.6	Golden Heart	687 000		10.3	0.30
	Cameco Corporation	12.3					

[1] refers to Mineral Resource Map of Saskatchewan, back pocket

[2] at closure, if mined out (operator first); at present, if not yet mined

[3] mined out

[4] published reserves in 1990

[5] production to June 30, 2001

[6] published reserves at start-up in 1995

[7] at suspension of mining, January 1997

[8] as of March 2001

[9] Anglo Rouyn mine tailings also contain 1.97 g/t (0.058 oz./ton) Ag, 0.15% Cu and 4.5% magnetite

[10] mineable reserves

[11] possible reserves

[12] does not conform to current CIM reporting standards

Evaporite Formation. The members tend to be carnallitic toward their margins. Grades of up to 80% carnallite are known south and southwest of the Quill Lakes area. Fuzesy (1982) reported carnallite-rich beds, probably of considerable areal extent, at Moose Mountain, Parkerview, Foam Lake, Nokomis, Wilkie and east of Watrous.

Other potential sources of magnesium include some of the saline lakes, such as Big Quill, Redberry, Basin, Little Manitou, Muskiki and Aroma. Magnesium content in the brines ranges from 0.157 to 2.3%. The concentration at any given time depends, to a large degree, on the local weather, which determines the amount of precipitation, dilution and evaporation.

Peat

The major peatlands of Saskatchewan cover about 4 million ha in a 200 km wide belt south of the Precambrian Shield edge and extending the width of the province (Figure 75; Scott *et al.*, 1980). The region consists of extensive uplands with relatively sparsely scattered peatlands, and intervening lowlands with widespread peatlands (Guliov, 1981).

Although sporadic investigations and small-scale production had probably taken place prior to 1945, the first serious examinations of the resource appear to have been conducted by Hastings (1945) and Leverin (1946). Troyer (1985) conducted the first regional investigation of peat resources in Saskatchewan with funds provided by the Canada-Saskatchewan Interim Subsidiary Agreement on Mineral Exploration, supplemented by independent provincial funding. He found that peatlands in the region west of the La Ronge–Montreal Lake region contain a large proportion of well-humified sedge fuel peat, generally with a sphagnum cover; that the sphagnum moss layer appears to be best developed in the La Ronge area; and that, although moss-peat resources are substantial, the fuel-peat potential is greater. The region to the east was not examined.

Commercial peat-moss production was initiated by the Carrot River Peat Moss Co. Ltd. in 1959. After a period of bog preparation and drainage, production of block-cut peat commenced. Blocks were arranged on the bog surface for drying and then transported to a plant near Carrot River where they were hammer-milled and bagged. In 1966, Asphalt Services Ltd. became a partner in the operation and the first shipment of floral peat was made to the tree nursery at Indian Head. Production was converted to a milling and vacuum operation in the late 1960s and market growth ensued during the 1970s. In 1980, the company was sold to the crown corporation, Saskatchewan Minerals, Peat Moss Division. In 1988, the operation was sold to Premiere Sask. Inc.

Premiere Sask Inc. remains the sole producer of peat moss in the province, with production at its Carrot River plant of more than 1 000 000 bales (about 27 kg each) in 2000. Production is by milling and vacuum harvesting. Drying is solar, although occasionally supplemented by artificial drying as needed. Premier has recently developed a bog immediately north of the plant, and an 800 ha bog is in the early stages of development near Tobin Lake, about 65 km north of the plant. The Tobin Lake bog has a reported thickness of 3.3 m of peat. Horticultural peat moss, the principal product in Saskatchewan, is marketed largely in western Canada and as far away as California and Hawaii in the United States. The finest material is useful in environmental applications.

Platinum-Group Elements

In the mid-1980s, Saskatchewan experienced a burst of platinum-group element (PGE) exploration. Between 1985 and 1988, numerous companies re-examined areas around known and previously explored mafic plutonic-hosted copper-nickel deposits, such as the Rottenstone mine and the Dunlop deposit, and around a host of known platinum-palladium showings in the Clearwater, Peter Lake and Wollaston domains. The Peter Lake Complex, in particular, is recognized as the second largest mafic-ultramafic complex in North America, with excellent PGE potential (Hulbert, 1988). Between 1995 and 1999, a second renewal of interest in PGE exploration occurred in the Clearwater and Rottenstone domains.

A second and potentially new type of PGE target in Saskatchewan is the platinum- and gold-bearing uranium veins of the Nicholson and Fish Hook Bay areas

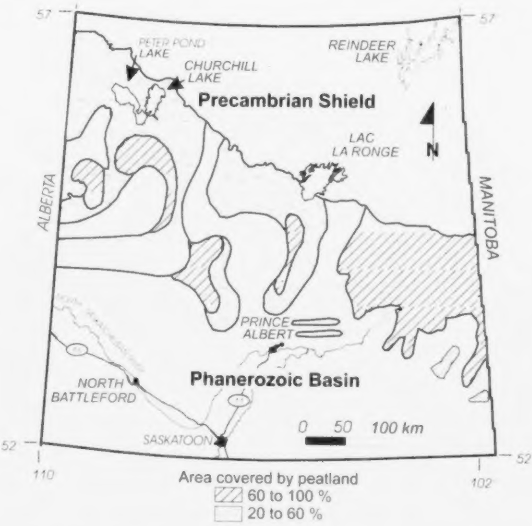


Figure 75 – Distribution of peat in central Saskatchewan.

on the north shore of Lake Athabasca, first recognized by Sibbald (1985). The veins are marked by complex mineralogy and geochemistry, features common to uranium deposits of unconformity type that characterize the Athabasca Basin and to uranium deposits associated with sandstone basins in other parts of the world. Of particular note in this context are the polymetallic uranium occurrences in Late Proterozoic metasediments in the Shaba Province of Zaire (e.g., the Shinkolobwe mine) and in the Early Proterozoic Coronation Sandstone in the South Alligator River valley of Australia's Northern Territory (e.g., the Coronation Hill mine). Both deposits contain uranium in association with gold, platinum and other metals.

Rare Metals and Rare-Earth Elements

The rare-earths are a moderately abundant group of 18 elements, specifically thorium, scandium, yttrium and the 15 lanthanide elements (Hedrick, 2001). There are more than 40 reported rare-earth element (REE) occurrences in Saskatchewan, but only a few have been extensively explored. Rare-earth element occurrences in northern Saskatchewan are divided into five types (Harper, 1987): 1) pegmatite-granite association, 2) metamorphosed paleoplacers, 3) apatite-allanite veins, 4) detrital heavy-mineral sands in the Athabasca Group (paleoplacers), and 5) diagenetic-hydrothermal deposits associated with unconformity-type uranium deposits. Most occurrences in northern Saskatchewan consist of monazite±xenotime and apatite in biotite-rich segregations in anatectic pegmatites and/or the adjacent gneisses (Harper, 1987). Assays typically range from 0.01 to 2.0% total rare-earth oxides, although the Alces Lake occurrence east of Uranium City gave values of up to 16% total rare-earth oxides.

History

World production of monazite is primarily from placer deposits in recent beach sands. An ilmenite-monazite occurrence in Archean granulite facies gneisses, at Archie Lake, 30 km east-southeast of Uranium City, is considered to represent an ancient metamorphosed deposit of that type (Harper, 1987). A 5 to 6 m thick stratabound zone has been traced over a strike length of 600 m. Geochemical values range from 0.1 to 15.7% total rare-earth oxides, along with 0.1 to 2.31% ThO_2 and up to 16% TiO_2.

The Athabasca Group quartz sandstones and conglomerates contain heavy-mineral layers, particularly in the strongly conglomeratic basal section. Detrital zircon, monazite and xenotime have been identified in some places, such as Maurice Bay (Harper, 1978) and Cluff Lake; however, these layers remain untested for REE-bearing paleoplacer deposits.

Yttrium associated with heavy rare-earth elements is concentrated in Athabasca Group sandstones at the Maw zone near Williams Lake in the southeastern part of the Athabasca Basin. Yttrium values ranging from 800 ppm to more than 2% were obtained from samples within a zone estimated to contain 336 000 t grading 0.25% Y_2O_3. A boulder sample above the Maw zone contained 6.76% Y, 6800 ppm Dy, 1700 ppm Yb, 3400 ppm Gd and 1300 ppm Tb. The mineralization consists of finely disseminated xenotime in silicified, brecciated sandstone, in an area partially coincident with a zone of dravitization and drusy quartz silicification (Quirt *et al.*, 1991). Masses of xenotime containing up to 10% Y occur in altered, clay-enriched Athabasca Group sandstones above the McClean Lake uranium deposits. These occurrences, together with enrichments in yttrium and REE in other Athabasca Basin uranium deposits, suggest a potential for 'unconformity-type' diagenetic-hydrothermal yttrium and REE deposits.

Current Exploration

Rare Metals

Tantalum is a refractory metal that is ductile, easily fabricated, has a high melting point, is highly resistant to corrosion by acids and is a good conductor of heat and electricity (Perron, 1994). It is principally used in the production of electronic components, mainly capacitors.

Regional lake-sediment and water geochemical sampling surveys conducted by the Geological Survey of Canada (GSC) in the Bright Lake area, 70 km northeast of Fond du Lac, produced the first tantalum anomalies in northern Saskatchewan (e.g., Friske *et al.*, 1994a, b). Values averaging 3 to 5 times regional background were reported in the Marchant Lake area, 50 km north of Stony Rapids.

Leader Mining International Inc. initiated an extensive mapping, prospecting and lithogeochemistry program on ground covering tantalum-cesium-rubidium-tungsten multi-element lake-sediment anomalies in the Bright Lake area in 2001. Systematic lake- and stream-sediment geochemistry, and lithogeochemistry were completed across the entire 15 by 40 km property. The mineralized source of the GSC anomalies is thought to be extensive tantalum-enriched pegmatite and granite intrusive rocks within amphibolitic gneisses near the boundary between the Dodge and Train domains. These rocks also contain elevated values of tin, cesium and rubidium. Pegmatite bodies associated with ophitic granite were identified, some up to 2 km long and 500 m wide. Detailed mapping was done in the summer of 2002, and 304 samples were submitted for geochemistry. Grab samples of pegmatite near Marchant Lake contained values up to 276 ppm Ta, 695 ppm Sn, 528 ppm Li, 5500 ppm Rb and 238 ppm Cs.

Rare-Earth Elements

Rare-earth elements are found concentrated in allanite- and apatite-bearing veins, fracture and shear zone systems within Archean granulitic gneiss terranes north of the Athabasca Basin, commonly near lithotectonic domain boundaries. Showings have been reported since the 1950s, but systematic exploration has only begun recently (Figure 41).

Some of the most extensive exploration for REE mineralization has occurred in the Nisikkatch-Hoidas lakes area (*Mineral Resource Map of Saskatchewan*, back pocket), 50 km northeast of Uranium City. In this area, 15 rare-earth apatite-allanite vein showings are found along a zone 10 km in strike length. Recent work at Hoidas Lake has revealed that mineralization is predominantly hosted by apatite, with lesser allanite and minor monazite. The mineralized zone is thought to consist of three parallel to subparallel shears up to 40 m in width. The main (middle) zone has a surface trace of 600 m and an average width of 4 m. The major rare-earth elements present are predominantly the light rare-earths, including cerium, lanthanum, neodymium and praseodymium, with lesser samarium. Composite samples revealed up to 7.12% Ce, 3.7% La and 2.47% Nd. Trench sampling of the 'main zone' returned grades up to 4.9% total rare-earth oxides over 3.2 m. Core sampling yielded similar results of up to 4.62% total rare-earth oxides over 5.2 m.

Exploration for rare-earth elements is more advanced to the west, in the Hoidas Lake area, some 40 km northeast of Uranium City. Daren Resources Ltd. began systematic exploration around the historic Hoidas Lake allanite showing in 1996. Great Western Minerals Group Ltd. is currently earning an interest in the property. Previous work by Daren had delineated a 10 km long fault trace with 26 separate REE showings. Trench sampling along a 400 m strike length on one showing, the JAK zone, outlined a central shear zone with an average of 4.9% total rare-earth oxides across 3.2 m. The zone was drilled along 450 m of strike and to a depth of 65 m in 2001. A resource calculation by Sierra Mineral Management Inc. in 2002 indicated 1.14 million t of ore containing a total of 48 926 g/t rare-earth oxides, including 20 675 g/t CeO_2, 9 851 g/t La_2O_3, 11 154 g/t Nd_2O_3, 3 000 g/t Pr_6O_{11} and 1 729 g/t Sm_2O_3.

Metallurgical tests showed that the deposit is amenable to open-pit mining, and metal extraction and concentration by cold-acid-leach techniques using nontoxic reagents. Recovery rates of 94% for total REE were reported, and metallurgical testing is ongoing. Rare-earth elements are grouped into fault-controlled skarn deposits, and fault-controlled, granite-hosted vein deposits. Both types are amenable to the leaching techniques.

Salt

For practical purposes, salt resources in Saskatchewan can be considered as unlimited. The principal source, and the only one presently exploited, is the thick, massive halite of the extensive potash-bearing Prairie Evaporite Formation in the southern half of the province. Saskatchewan producers and products are shown in Table 20. Salt is produced as a by-product at five potash mines, and at two solution mines where salt is the principal product. Four of the by-product producers utilize potash tailings as their feedstock, while the fifth uses co-product brine from the nearby Belle Plaine solution potash mine as its feedstock.

Salt (sodium chloride) occurrences in Saskatchewan are of three types:

- **Saline springs:** These are common in the region flanking the north slope of the Pasquia Hills in east-central Saskatchewan, near the limit of Devonian rocks (Simpson and Dennison, 1975). A few other saline springs occur in scattered localities in western Saskatchewan and along the northern limit of the Athabasca Basin.

- **Subsurface formation brines:** Generally, the salinity of subsurface Phanerozoic formation brines increases southward and southeastward toward the centre of the Williston Basin. Maximum chloride contents in excess of 189 000 mg/l have been recorded in the deeper clastic aquifers, and about 38 000 mg/l in the shallower and younger aquifers of the Mesozoic (Simpson and Dennison, 1975).

- **Massive halite:** Resources of massive halite occurring in beds of Devonian age (cf. potash distribution in Figure 45) are practically unlimited. The Middle Devonian Prairie Evaporite extends over most of the southern third of the province and is the largest salt deposit. The formation ranges in depth from 400 to 2740 m, and averages 120 m in thickness (Figure 46). Other Devonian halite deposits of economic significance are the Dawson Bay–Hubbard Evaporite (Figure 45) and the Duperow–Flat Lake halite (Dunn, 1975; Lane, 1959, 1964). Deposits of lesser significance occur in the Mississippian Poplar and Ratcliffe beds of southeastern Saskatchewan. Thick halite deposits are of economic significance not only for their salt resources but also as a medium for the development of salt caverns for the storage of natural and manufactured gases. Massive halite and mixed halite-sylvite-carnallite deposits of the Middle Devonian Prairie Evaporite represent, by far, the largest salt resource in the province.

The salt requirements of the early plains settlers and traders were satisfied, from about 1800 to 1876, by salt springs west of Lake Winnipegosis and Lake Manitoba. Men freed from Hudson's Bay Company service and employees of the Northwest Company evaporated the brines in iron kettles and troughs, and supplied the salt to the Hudson's Bay Company posts from Norway

House to Fort Qu'Appelle and to the Red River Settlement (De Lury and Cole, 1928). With the arrival of the railway in 1882, Ontario became the main supplier of salt to the west.

Table 20 – Saskatchewan salt producers.

Operator	Location	Type of Operation	1995 capacity (tonnes/ year)[1]
Canadian Salt Co. Ltd.	Belle Plaine	Produces fine salt from by-product brine from nearby IMC Kalium potash operation	170 000
Sifto Canada Inc. (a division of IMC Salt)	Unity	Brining for vacuum-pan evaporation	180 000
Sterling Pulp Chemicals Ltd.	Saskatoon	Brining for caustic soda, chlorine and sodium chlorate	82 000
NSC Minerals Inc.	Rocanville	By-product rock salt from potash tailings	140 000
NSC Minerals Inc.	Vanscoy	By-product rock salt from potash tailings	140 000
IMC Salt (a business unit of IMC Global Inc.)	Colonsay	By-product rock salt from potash tailings	328 000
IMC Salt (a business unit of IMC Global Inc.)	Esterhazy (K-1 & K-2)	By-product rock salt from potash tailings	180 000

[1] figures from Morel-à-l'Huissier (1995), confirmed and updated by personal communications with mine operators

The earliest known production of salt in Saskatchewan was by the Senlac Salt Co. in about 1920 at Salt Lake, south of Senlac in west-central Saskatchewan. A small solar-evaporating system was replaced after a short time by three large, open, evaporating pans heated by coal fires. The operation closed down after two or three years.

In 1932, while drilling for oil in the Simpson area, the Simpson Oil and Gas Co. encountered salt brine at a depth of 1067 m (Worcester, 1935). The brine was likely associated with the Upper Devonian Souris River Formation, where massive halite deposits of the Davidson Member are present. The company established a small evaporating plant with a capacity of several tonnes of salt per day. Production ceased in 1935.

In 1946, salt and potash of the Prairie Evaporite were encountered in the Verbata No. 2 well near Unity, in west-central Saskatchewan. By May 1949, the Prairie Salt Co. had developed a salt-brining operation there and made its first shipment of product. Sifto Canada Inc., a subsidiary of IMC Salt, now operates the plant. Saskatoon Chemicals commenced a salt-brining operation from the Prairie Evaporite near Saskatoon in 1968 for caustic-soda and chlorine production. This operation was acquired by Sterling Pulp Chemicals Ltd. in 1998. The International Minerals and Chemical Corporation (Canada) Ltd., engaged in potash production since 1961, also produces by-product salt at two potash mines for road-ice control. Road salt is also produced from potash mine waste by NSC Minerals Inc. at Rocanville and Vanscoy. The Canadian Salt Company Ltd. has utilized by-product salt from the nearby Kalium Chemicals solution potash mine since 1969 for various products, including food-grade salt and medicated salt blocks for livestock.

As of 2000, Saskatchewan accounted for 6% of total Canadian salt production. With minor exceptions, annual salt production has grown steadily in the past 30 years, from about 200 000 t to more than 700 000 t, while value has risen from about $3 million to more than $20 million (Figure 76).

Silica Sand

High-purity silica sands are widespread and relatively near the surface over large regions of the northern Phanerozoic Basin. Two stratigraphic intervals, the Lower Cretaceous Mannville Group and the Ordovician Winnipeg Formation, have been explored and utilized as silica-sand resources. Scattered occurrences of glacial or recent lacustrine outwash or beach sands of somewhat lower quality are also known.

The most recent research on the major silica-sand deposits in the province was that carried out under the Canada-Saskatchewan Partnership Agreement on Mineral Development (1990-1995). Gent (1993) conducted extensive testing on bulk samples from the three major deposits. Work included granulometry, chemical analysis, heavy-mineral content, X-ray diffraction analysis, brightness and reflectance tests, and fracture sand analyses. In conjunction with the same project, IMD Laboratories was contracted to conduct extensive beneficiation tests to determine the potential application of the sands, particularly in high-tech uses.

Beneficiation tests conducted on both Mannville Group and Winnipeg Formation sands demonstrated that they can be effectively upgraded by attrition scrubbing, magnetic separation, acid leaching and calcination. The resulting product is similar to, or better than, the Quintus grade of Unimin Corporation (Table 21); impurities represent less than 0.01% of the product.

Important silica-sand resources of the Ordovician Winnipeg Formation are exposed in scattered outcrops in the Hanson Lake–Deschambault Lake area. Among the earliest works on the Winnipeg Formation were those

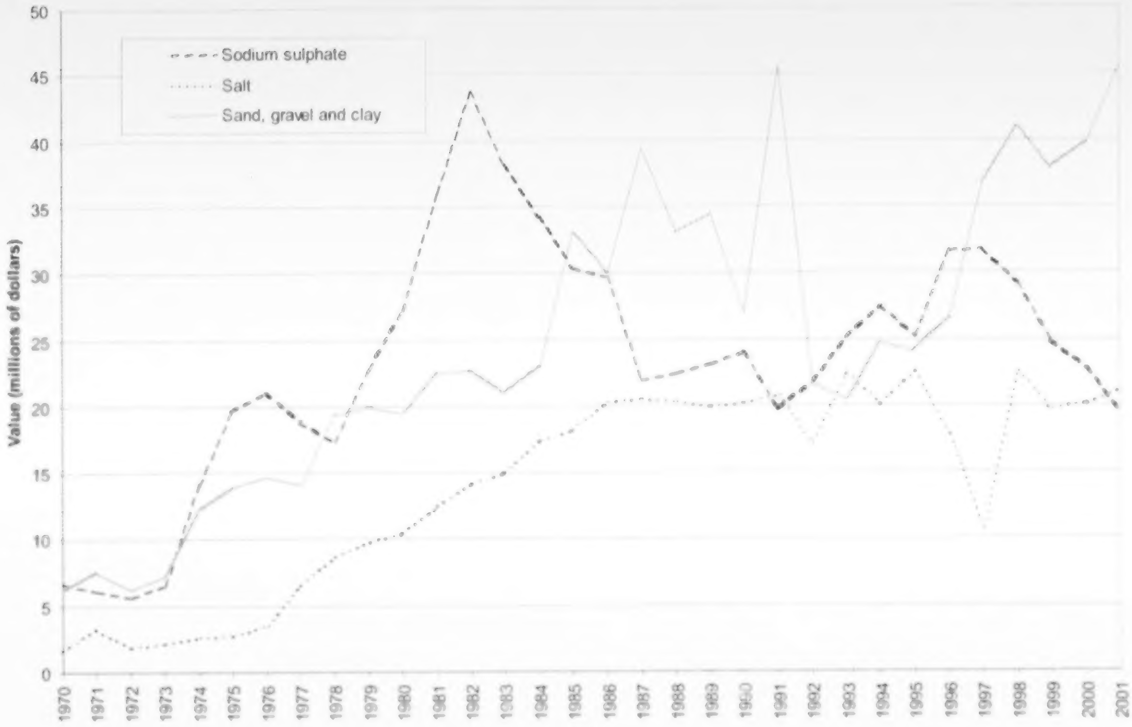


Figure 76 – Value of the Saskatchewan salt, sodium sulphate, and sand and gravel production, 1970-2000.

of Kupsch (1952) and Byers (1957). Later, Paterson (1971) studied the formation on a regional stratigraphic basis. Holocene Resources Ltd. conducted an evaluation of the Winnipeg sand for its potential as a hydraulic fracturing sand and a source of industrial silica. More recently (1988-1989) SaskOil, Wascana Energy Inc. and Nexen Inc. conducted extensive testing of the Ordovician sands for frac-sand application.

Where overburden is particularly thin, erosion has, in places, exposed significant sections of the Mannville Group sands, some of which are of industrial importance. The major deposits of silica sand are located along the Red Deer River, approximately 48 km northeast of Hudson Bay and over an extensive region south of Wapawekka Lake and Lac La Ronge. Babey (1955) reported a silica content of 97.4 to 98.5% in untreated Red Deer River sands. Washed and tabled product ranged from 99.0 to 99.6% silica. Sieve analyses indicated 77.4 to 86.9% in the -20 to +65 mesh range. Babey (1955) and Collings and Andrews (1986) agreed on the potential value of the sands for glass and as foundry material.

Cretaceous silica sands along the Red Deer River were discovered by the Howryschuk brothers in about 1941. Worcester (1943) conducted the first examination of

Table 21 – ICP chemical analyses of major-element oxides and trace-element impurities doe calcined and leached silica-sand samples that have been beneficiated by attrition scrubbing and magnetic separation (ICP method). Silica content is greater than 99%.

Analyte	Hanson Lake (ppm)	Red Deer (ppm)
Al_2O_3	180	190
CaO	<20	<20
MgO	<2	<3
Na_2O	<5	<5
K_2O	10	13
Fe_2O_3	50	60
MnO	2	3
TiO_2	70	160
P_2O_5	<10	<10
Cr	<1	<1
Sr	<1	<1
Y	<1	<1
Zr	32	19
Nb	<1	<1
Ba	2	4

the deposit in 1942, followed by Wickenden (1945). The Canada Department of Mines and Technical Surveys performed beneficiation and evaluation work on the sands periodically between 1946 and 1986. Babey (1955) and Beck (1974) carried out investigations for the province. Lower Cretaceous silica sands in the Wapawekka Lake and Bow River areas (Figure 77) were examined by Pearson (1961) and Hudson (1961), respectively. Langford (1973) recognized their economic potential for silica and associated kaolinite, and indicated the immensity of the resource. Analyses of controlled samples taken by Saskatchewan Energy and Mines (Gent, 1993) are presented in Table 22.

Since their discovery, the Red Deer River deposits have gone through several cycles of dispositions by industry, but little or no work had been conducted until Prairie Silica Ltd., King Resources Ltd. and Northland Distribution and Supply Co. took an interest between 1973 and 1983. In 1986, Red Deer Silica Inc. began production of silica sand from the Mannville Group deposits along the Red Deer River northeast of Hudson Bay. The sand is screened and washed at the quarry site and marketed primarily for golf course bunkers. The company is pursuing other market opportunities, including glass, foundry, filtration and silicon applications.

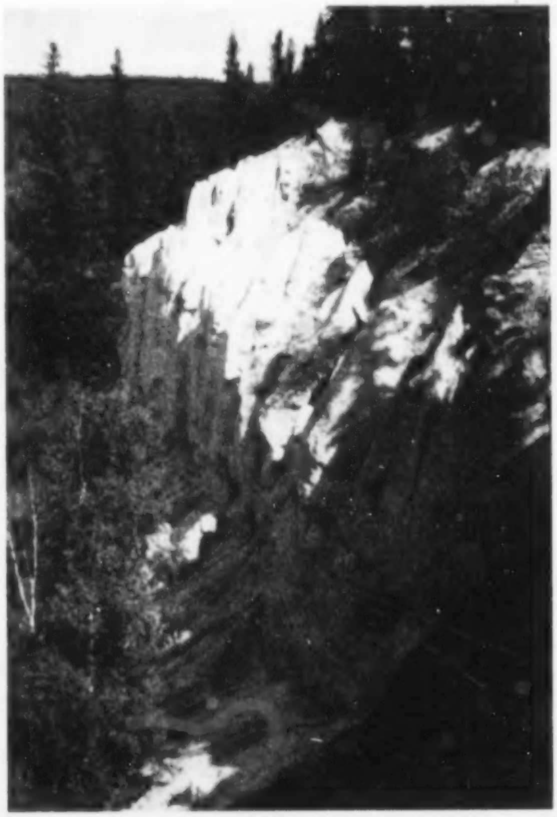


Figure 77 – Lower Cretaceous silica-sand outcrop, Nipekamew River.

Hudson Bay Mining and Smelting Co. Ltd. has quarried some 7 million t of sand for flux in its Flin Flon zinc smelter since 1933. A variety of sands have been used for this purpose, including the Ordovician Winnipeg Formation, Lower Cretaceous Mannville Group and glaciofluvial sands.

In 2000, Hanson Lake Sand Corporation, a subsidiary of Daren Industries Ltd., began pilot-scale production of Winnipeg Formation sands (Figure 78) at Hanson Lake for petroleum-well hydrofracturing propping media (frac sand). Prior to commencing production, the company announced that it had secured agreements with two major western Canada frac-sand distributors to purchase all production meeting American Petroleum Institute (API) specifications for frac sand. The company operated the pilot plant from April to August of 2001 and reported meeting the objective of producing frac sand that met API specifications (Table 23); establishing an effective distribution and delivery network; and selling all of the pilot-plant production of 20/40 frac sand. The pilot plant was shut down in September 2001, and the company sought funds for ramping up to full production. Unable to raise additional funds, the company sought bankruptcy protection.

Sodium Sulphate

Sodium sulphate is used in the manufacture of detergents, carpet fresheners and deodorizers, and float (plate) glass, and in textile dyeing. Two Saskatchewan companies combine sodium sulphate and potash in the value-added manufacture of potassium sulphate, which

Table 22 – Average size distribution and other data for sand from the Nipekamew River site.

Size interval	Proportion (%)	Average SiO$_2$ (%)	Average Kaolin (%)
Upper Unit (13 m)			
-5 +10	9.7	98.62	1.25
-10 +18	14.4	98.74	1.15
-18+35	25.4	98.35	1.55
-35 +60[1]	19.3	97.33	2.5
-60 +100	10.2	95.6	5.7
Lower Unit (4 m)			
-60 +100	32.7	99.56	0.53
-100 +200	41.8	98.31	1.58
-200	11.5	62.29	39.1

[1] tromelling and washing of one sample from the -35+60 mesh fraction increased the silica content from 98.34% to 99.03%

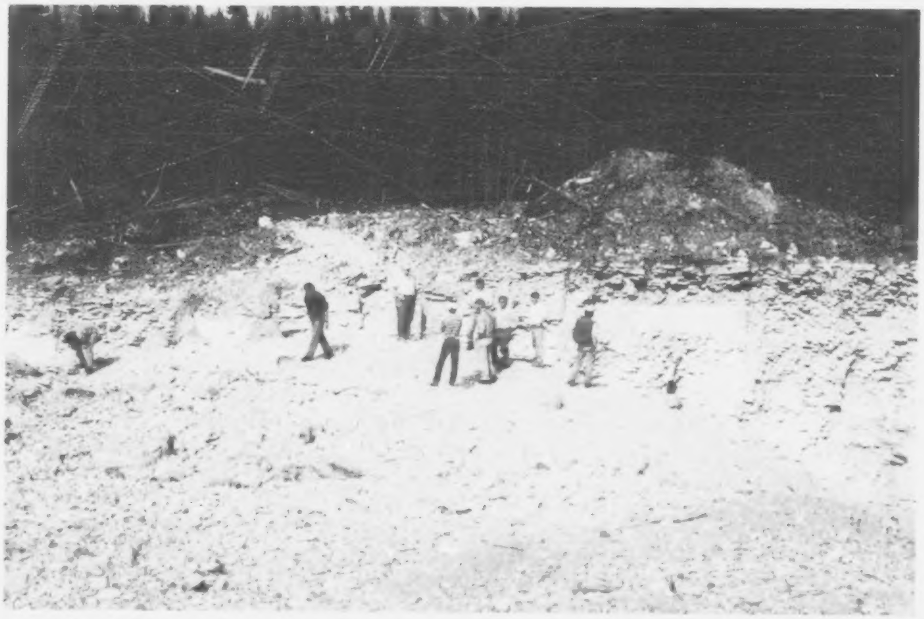


Figure 78 – Hanson Lake Sand Corporation test quarry. Dolomite cap rock has been removed to expose underlying sand.

is used as fertilizer for chloride-sensitive crops and a variety of industrial applications. Sodium sulphate is extracted from evaporite deposits in groundwater-fed postglacial hypersaline lakes that occupy internally drained basins.

Discovery of sodium- and magnesium-sulphate salts resulted from a search for potash in the alkali lakes. Because of the potash shortage during World War I, mineral rights at many of these lakes were claimed in 1918. Most of the claim holders allowed their claims to lapse when no potash was found. A few recognized the potential for substantial deposits of Epsom and Glauber's salts.

The earliest attempt at alkali recovery was made by the Canadian Salt and Potash Co. of Canada Ltd. in 1918 to 1919 at Muskiki Lake. Shortly thereafter, from 1921 to 1924, the Canada Department of Mines embarked on extensive surveys of the alkali lakes and their deposits. This work (Cole, 1926) was instrumental in the development of the resource. Tomkins (1954) added significantly to the description of the major deposits and to an understanding of the technology of production. Recent research by Last (1983), Last and Schweyen (1983), Slezak and Last (1984), and Kelley and Holmden (2001) examined the geology, sedimentology and geochemistry of the saline lakes of the Great Plains region.

Table 23 – Results for frac sand from the Hanson Lake Sand Corporation operation, compared with API specifications for frac sand.

Parameter	–20 to +40 mesh				–40 to +70 mesh			
	API spec	Hanson Lake			API spec	Hanson Lake		
		Av.	Max.	Min.		Av.	Max.	Min.
Sphericity	0.60 (min.)	0.83	0.85	0.81	0.60 (min.)	0.81	0.84	0.78
Roundness	0.60 (min.)	0.69	0.7	0.67	0.60 (min.)	0.64	0.67	0.61
Turbidity (FTU)	250 (max)	20	20	nd	250 (max.)	nd	nd	nd
Acid solubility (wt. %)	2.0 (max.)	0.79	0.8	<0.5	3.0 (max.)	<0.5	<0.5	<0.5
Crush testing fines (wt. % at 4000 psi)	14.0 (max.)	? 1.0	13.2	0.56	8.0 (max.)	6.53	6.97	6.09

The area extending roughly parallel to The Missouri Coteau across northwestern North Dakota, northeastern Montana, southern Saskatchewan and east-central Alberta (Figure 79) contains thousands of internally drained basins, occupied by either ephemeral (playa) or perennial bodies of water (Last and Slezak, 1988). The basins that host evaporite mineral deposits are fed by groundwater. Active seeps and springs are common features on the margins and in the beds of the closed-basin lakes. Evaporative concentration takes place during the warm, dry, windy summers. Some lakes (playas), through evaporative pumping, dry out completely each summer, whereas perennial saline lakes may precipitate evaporites through 'freeze-out' of very soluble salts with declining ambient temperatures in the autumn. The salts thus produced are known as the seasonal or intermittent crystal bed, which may be partially or wholly dissolved during the following spring and summer. Partial seasonal dissolution results in a net accumulation of permanent crystal beds, some of which are of exceptionally high grade, containing in excess of 90% salts of sodium and magnesium.

In general, the evaporite deposits are dominated by mirabilite ($Na_2SO_4\cdot10H_2O$), with varying proportions of thenardite (Na_2SO_4), bloedite ($Na_2Mg(SO_4)2\cdot4H_2O$), epsomite ($MgSO_4\cdot7H_2O$) and other salts. Permanent crystal beds are typically 1 to 5 m thick, but may, in some lakes, reach far greater thicknesses (e.g., more than 30 m in Ingebrigt Lake near Fox Valley in southwestern Saskatchewan). The principal impurities in the salt beds are clay, silt, sand and organic matter, including the remains of algae and various high-salinity aquatic fauna. Commercial extraction utilizes the accumulation of salts in saline lakes (Figure 80).

Tomkins (1954) identified 21 major, natural sodium-sulphate deposits in Saskatchewan with more than 500 000 t of reserves each. He described 11 others in the 100 000 to 500 000 t range and 13 of less than 100 000 t. At least 25 others are known but have not been investigated in detail (Cole, 1926). The total resource of anhydrous sodium sulphate contained in the 21 largest deposits was estimated by Tomkins at approximately 50 million t. The distribution of most of the deposits is shown in Figure 79.

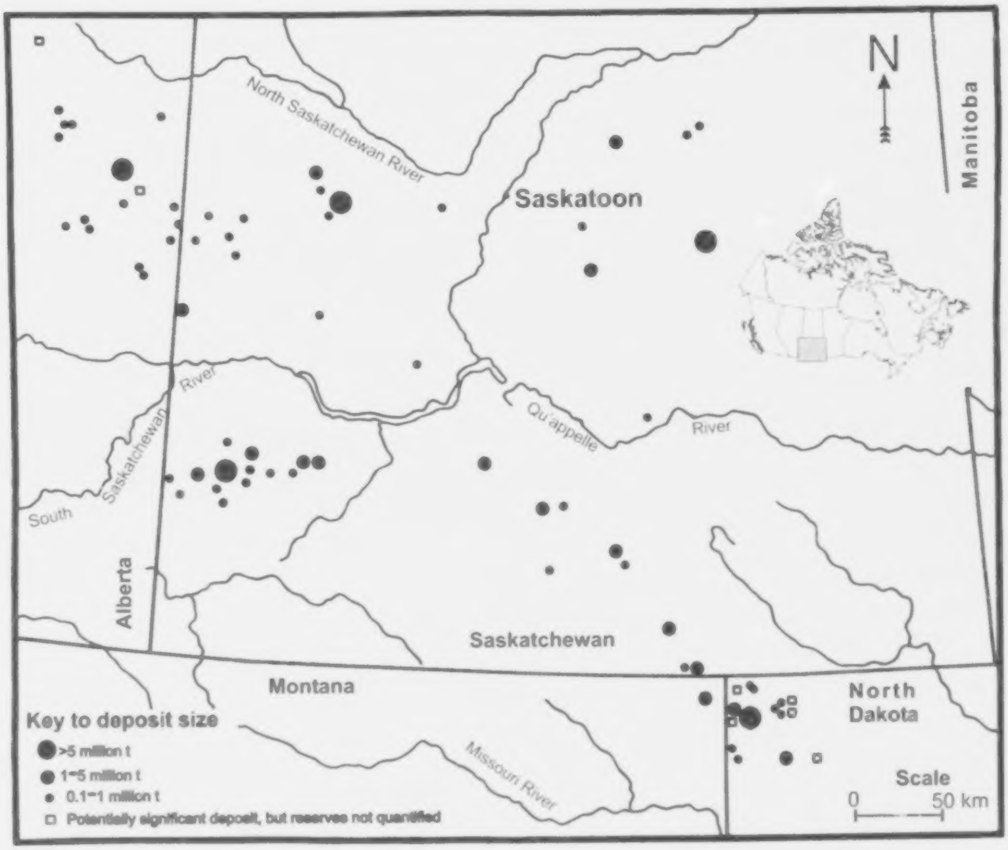

N
Manitoba
North Saskatchewan River
Saskatoon
South
Saskatchewan
River
Qu'appelle
River
Alberta
Saskatchewan
Montana
North
Dakota
Missouri River
Key to deposit size
>5 million t
1–5 million t
0.1–1 million t
Potentially significant deposit, but reserves not quantified
Scale
0
50 km

Figure 79 – Distribution and size of sodium-sulphate deposits of the northern Great Plains (from Last and Slezak, 1987).

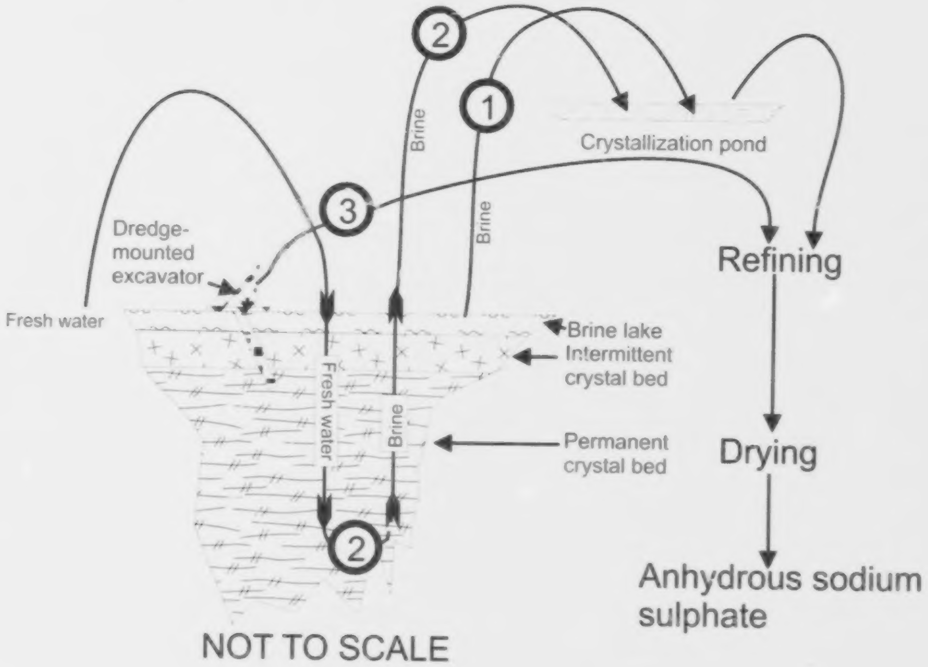


Figure 80 – Schematic cross-section of an idealized Saskatchewan sodium-sulphate deposit. Mining methods illustrated are 1) evaporative concentration of lake brine in crystallization pond, followed by precipitation of crystals of Glauber's salt (mirabilite) as the brine cools in autumn; 2) solution mining of thick crystal beds, with brine return being treated as in (1); and 3) dredging of lake-bottom crystal beds (from Kelley and Holmden, 2001).

Since the first attempt at sodium-sulphate mining, more than twenty companies have been involved in development work over the past 80 years. Four are operating today. Millar Western Industries Ltd. produces at the Palo mine on Whiteshore Lake, northwest of Biggar, and Saskatchewan Minerals (a division of Dickenson Mines Ltd.) operates a plant at Chaplin Lake (Figure 81). Both produce anhydrous sodium sulphate as a final product. Prairie Sulphate Corporation Inc. extracts Glaubers salt from Horseshoe Lake near Alsask and processes it with potash to produce potassium sulphate. Big Quill Resources Inc. combines potash with 1) sodium sulphate purchased from others to produce agricultural grades of potassium sulphate, and 2) dilute sodium-sulphate brine from Big Quill Lake to produce high-purity industrial grades of potassium sulphate. Two sodium-sulphate plants currently sit idle. Ormiston Mining and Smelting Co. Ltd. closed the Ormiston Lake operation, south of Moose Jaw, in 1999 and placed the recently refurbished plant on care-and-maintenance. Saskatchewan Minerals Ingebrigt operation, near Fox Valley, was closed in early 2001.

Saskatchewan producers of natural sodium sulphate compete in the marketplace with sodium sulphate that is a by-product of several manufacturing processes. Historically, the by-product material has come from the manufacture of rayon, but the 1990s saw new material from lead-acid battery recycling and the chromium

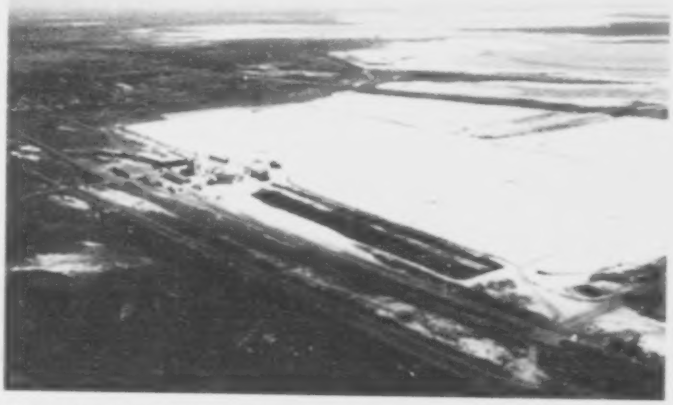


Figure 81 – Saskatchewan Minerals sodium-sulphate plant at Chaplin Lake.

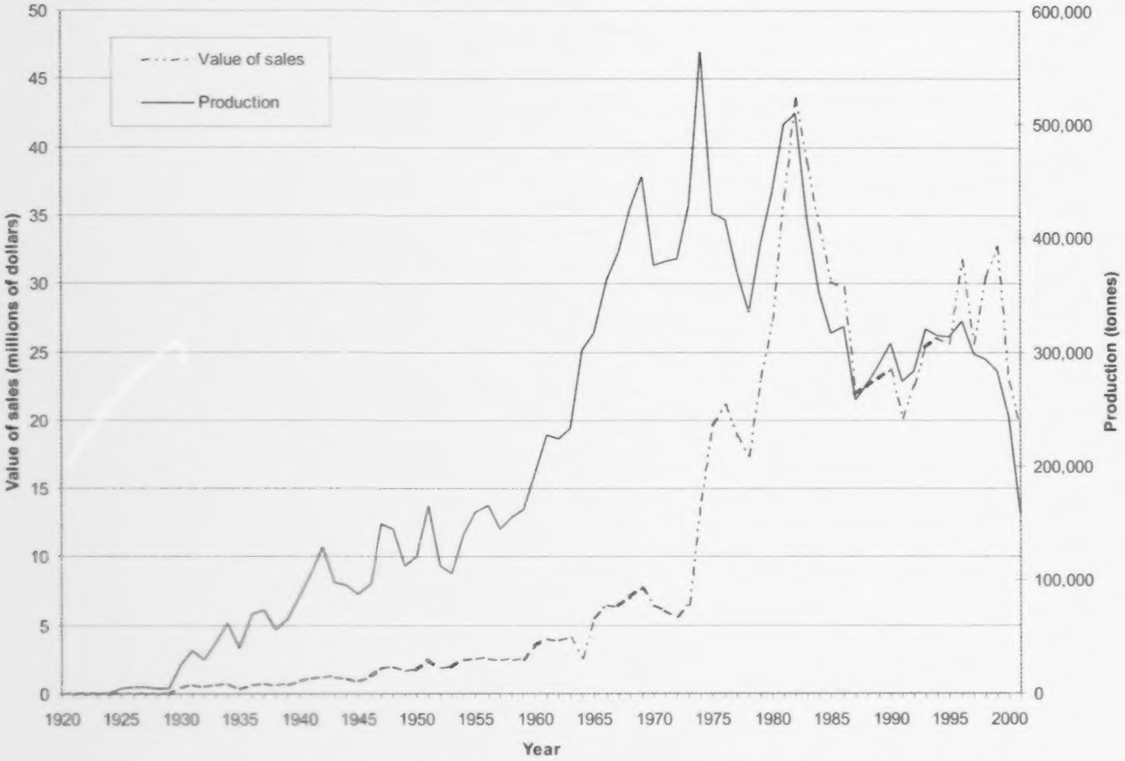


Figure 82 – Sodium sulphate production in Saskatchewan, 1920-2000.

chemical industry. Because their market competition is the by-product of primary industries, the fortunes of the natural sodium-sulphate producers have historically run somewhat countercyclical with respect to the general economy. Peak production levels, and total value, for the Saskatchewan sodium sulphate industry occurred in the early 1980s (Figure 82).

Exploration and Development Regulations

Mineral Ownership

The lands that constitute the Province of Saskatchewan were acquired by the Government of Canada in 1870, through the surrender of the Hudson's Bay Company charter. In return for surrendering its charter, the company received grants for lands in the vicinity of their trading posts, as well as grants totalling 1/20th of the land within the southern agricultural belt. These Hudson's Bay Company grants included the surface rights as well as the underlying mineral rights.

Following acquisition of the former Hudson's Bay Company lands, the federal government implemented a series of land policies designed to encourage settlement of its newly acquired western territories. This included the issuance of grants to railways to finance rail construction, and land grants to land-settlement companies and homesteaders. In the early days of settlement, most of these grants included the underlying minerals.

In 1887, all new land grants west of the Third Meridian, in the area that is now Saskatchewan, were made subject to a reservation of minerals in the Crown and, in 1890, this was extended to the area east of the Third Meridian. After 1890, all new land grants issued to homesteaders by the federal government under the *Dominion Lands Act* included a reservation of minerals. When the Province of Saskatchewan was created in 1905, jurisdiction over natural resources was retained by the Canadian government and was not relinquished to the province until October 1, 1930, under the *Natural Resources Transfer Agreement*. Between 1930 and 1939, the province inadvertently alienated additional Crown mineral rights during disposition of Crown lands to individuals when transfers of title did not specifically include reservation of minerals in the Crown.

At present, approximately 89% of the 65 million ha of mineral rights in Saskatchewan are owned by the provincial government. Approximately 9% are owned by private interests. Most of the private mineral rights are located in the southern, surveyed portion of the province, where private ownership accounts for approximately 18% of the surveyed land base. In the unsurveyed, northern part of Saskatchewan, virtually 100% of the minerals are owned by the Crown. The balance of the mineral rights in the province (approximately 1 million ha) are owned by the federal government. These mineral rights are located primarily beneath Indian reserves and national parks.

Prior to October 1930, the disposition of Crown minerals in Saskatchewan was under the jurisdiction of the federal government, and exploration and development were controlled by federal legislation. Following the transfer of natural resources to provincial control, the province implemented a *Mineral Resources Act*, under which a series of mineral-specific regulations were formulated to govern disposition, exploration and development of Crown-owned minerals.

Currently, exploration and development of minerals are governed by *The Mineral Resources Act, 1985*, which applies to all mineral resources in Saskatchewan, and *The Crown Minerals Act*, which applies only to Crown-owned minerals. Crown mineral rights are administered by Saskatchewan Industry and Resources. Where minerals are owned by private individuals, rights to the minerals must be negotiated with the private landowner. Copies of all Saskatchewan Acts and Regulations governing the administration of Crown minerals are available for viewing or download, at no charge, from www.qp.gov.sk.ca.

Metallic and Precious-Mineral Tenure

Mineral tenure requirements related to the exploration for, and development of, Crown-owned metallic minerals (base and precious metals, diamonds, uranium and rare-earth elements) are governed by *The Mineral Disposition Regulations, 1986*. Any person or company may acquire a mineral disposition, and there are no residency or licensing prerequisites. There are three types of mineral tenure or disposition: permit, claim and lease. Their main characteristics are summarized in Table 24.

Crown mineral dispositions grant the holder the exclusive right to explore that area for minerals. Crown mineral leases are required when mineral production from an area occurs. Mineral permits are generally used by companies carrying out reconnaissance programs. They are acquired by map staking, have a two-year term and may be converted to claim status. Mineral claims and leases may be applied for on any available Crown mineral land. In the unsurveyed, northern part of the province, where the Precambrian Shield is extensively exposed, claims and leases must be staked out on the ground. In the southern, surveyed part of Saskatchewan, claims and leases are applied for by map staking.

Disposition holders keep their properties in good standing by performing annual assessment-work expenditures and submitting reports documenting the results. This information remains confidential for a three-year period. When a mineral lease is brought into commercial production, an annual rental is paid in lieu of the work-expenditure requirement.

Industrial Mineral Tenure

The disposition of rights to Crown-owned industrial minerals is governed by four sets of mineral-specific regulations: *The Coal Disposition Regulations, 1988*, dealing with coal; *The Alkali Mining Regulations*, dealing with surface accumulations of soluble mineral salts, principally sodium sulphate; *The Subsurface Mineral Regulations, 1960*, dealing with soluble mineral salts occurring more than 200 feet (61 m) below the surface (i.e., bedded salt and potash minerals); and *The Quarrying Regulations, 1957*, dealing with defined substances that can be quarried, including building stone, limestone, shale, clays and silica sand, but excluding aggregates, which are considered part of the surface.

Under these regulations, dispositions are made by permits, which cover large areas for short periods of time for preliminary exploration purposes, and by leases for more detailed exploration or production. Alkali minerals are held only under lease, except for individuals involved in local cottage industries, who may be issued nonexclusive permits for limited quantities of material. Permits and leases are applied for in the surveyed area by referencing maps and legal land descriptions, and in the unsurveyed area by ground staking. Permits are held by satisfaction of a work-expenditure requirement, and leases are held by an annual rental, based on size.

For sand, gravel and structural clays, *The Sand and Gravel Act* deems sand, gravel and structural clays, which can be quarried, to belong to and pass with ownership of the surface. The disposition of these materials on Crown lands is now done through surface leases administered by the Department of Agriculture, Food and Rural Revitalization in southern Saskatchewan, and the Department of Environment in northern Saskatchewan.

Petroleum and Natural Gas

Disposition of petroleum and natural-gas rights is governed by *The Petroleum and Natural Gas Regulations, 1969*. Under these regulations, dispositions are advertised and sold at public sales that are currently held six times per year. Companies request specific lands to be posted as one of three types of dispositions (special exploratory permit, exploration license or lease).

Special exploratory permits have the largest area (up to 200 000 ha) of the three types of dispositions. They grant the holder the right to explore for oil and natural gas. If oil and/or natural gas are discovered on the lands, the holder of the permit must apply for a lease, which allows production. The maximum amount of permit lands that can be leased is 50% of the Crown lands in the permit. Special exploratory permits are awarded on the basis of competitive bidding, in the form of work commitments.

The second type of disposition, the exploration license, applies to smaller land areas (up to 9324 ha) and has terms ranging from two to four years, depending on a license's location in the province. This type of disposition requires the holder to drill a well or wells in order to earn the right to convert the disposition to a lease at the end of the term. The amount of lease land earned is based on the sum total of depth drilled for all wells drilled within the exploration license. Production of oil or gas is allowed from this disposition.

The last type of disposition is the petroleum and natural-gas lease. Leases convey the right to produce oil and natural gas. An 'oil only' or 'gas only' lease is sold if one of these commodities is already under lease. Leases have a primary term of five years. Those surveyed sections of the lease containing at least one pro-

Table 24 – Characteristics of the three types of mineral disposition.

Disposition type	Term	Recording fee (C$)	Assessment work costs/rentals (C$)	Size
Permit	2 years; nonrenewable	$0.15/ha; $15,000 refundable cash deposit	$1.25/ha, yr. 1 $4.00/ha, yr. 2	10 000–50 000 ha[1]
Claim	2 years; renewable	$0.30/ha	$12/ha, yr. 2–10 $25/ha, yr. 11 on	16–6 000 ha
Lease	10 years; renewable	$100	Nonproducing: $25/ha, yr. 1–10 $50/ha, yr. 11–20 $75/ha, yr. 21 on Producing lease Rentals of $10/ha	16–6 000 ha

[1] hectares (1 hectare = 2.471 acres)

ducing well are continued to the base of the producing zone until production ceases.

Exploration and development activities, such as seismic surveys and the drilling of wells, are subject to licences issued in accordance with *The Seismic Exploration Regulations, 1999* and *The Oil and Gas Conservation Regulations, 1985*.

Land-Use Planning

Saskatchewan Industry and Resources and the mining and oil and gas industries participate in two main types of planning initiatives: 1) regional integrated land-use planning, and 2) the Representative Areas Network (RAN) program.

Regional Land-Use Plans

Integrated land-use planning in the northern part of the province is initiated and led by Saskatchewan Environment and Resource Management (SERM). Saskatchewan Agriculture and Food (SAF) leads the land-use plans on lands under their management in the southern part of the province. The planning processes usually involve only Crown surface lands. The public advisory planning committees that develop the plan recommendations consist of representatives from stakeholder and community groups. Representatives of provincial government departments act in advisory and resource capacities.

Important considerations for the mining and oil and gas industries are the potential restrictions on surface access and activities that may result from the planning process. These include the selection of RAN sites; regional zoning on land use; buffers around water bodies and historical, cultural, archeological and ecological sites; and the establishment of wildlife-management areas. Other important issues that may be discussed include the development and closure of temporary roads and trails, compensation, public consultation and environmental monitoring. It is therefore vitally important that industry is adequately represented on the public advisory committees.

Government departments and agencies implement a plan after it has been completed and approved. A public committee remains in place to oversee the plan development. The plan may be revised to address new issues and changing circumstances. Full reviews are normally done every five years.

Representative Areas Network Program

The Government of Saskatchewan, with SERM as the lead department, initiated the Representative Areas Network (RAN) program in 1996. The RAN is composed of lands and waters selected and designated to represent the natural ecological and biological diversity of the province and managed to retain that diversity. The RAN sites act both as reservoirs of biological diversity and as benchmarks for comparison with the more heavily used landscape. There are eleven ecoregions in the province to represent. The RAN includes the national and provincial parks and other similar types of designations, as well as those sites specifically designated under the program.

Other government departments, especially Saskatchewan Industry and Resources (SIR), are involved in the RAN site-selection process, as well as industry and the general public. A structured process is used for the review of site proposals by SIR, including a technical evaluation of the mineral potential (*see* 'Mineral-Resource Assessments' section) and industry review and approval. As exploration and development are normally not allowed activities in designated RAN sites, the goal is to locate the sites in areas of low assessed mineral potential. Fieldwork may be undertaken to enhance geological knowledge in areas where the information is too limited to adequately assess the mineral potential.

Mineral-Resource Assessments

Regional mineral-resource assessments (MRAs), of known and potential mineral and petroleum (oil and gas) resources, are carried out to provide technical information to the integrated land-use planning and RAN programs, and for other land-use initiatives. Appraisals are normally done at a scale of 1:250 000 for individual NTS map sheets. Developed by the Ontario Geological Survey (Rogers and Hart, 1995), the mineral assessment methodology is qualitative and integrates, through a structured process, geoscience and mineral and petroleum exploration and deposit information with assessment criteria derived from descriptive mineral-deposit models (Rogers *et al.*, 1995). Additions have been made to the procedure to address the assessment of some Saskatchewan deposit types. Digital geological compilation maps, mineral and petroleum resource-assessment maps, and summary reports are the assessment products. These are available to the public.

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Saskatchewan Industry and Resources
Saskatchewan Geological Survey

Composite Aeromagnetic Total Field and First Vertical Derivative Map

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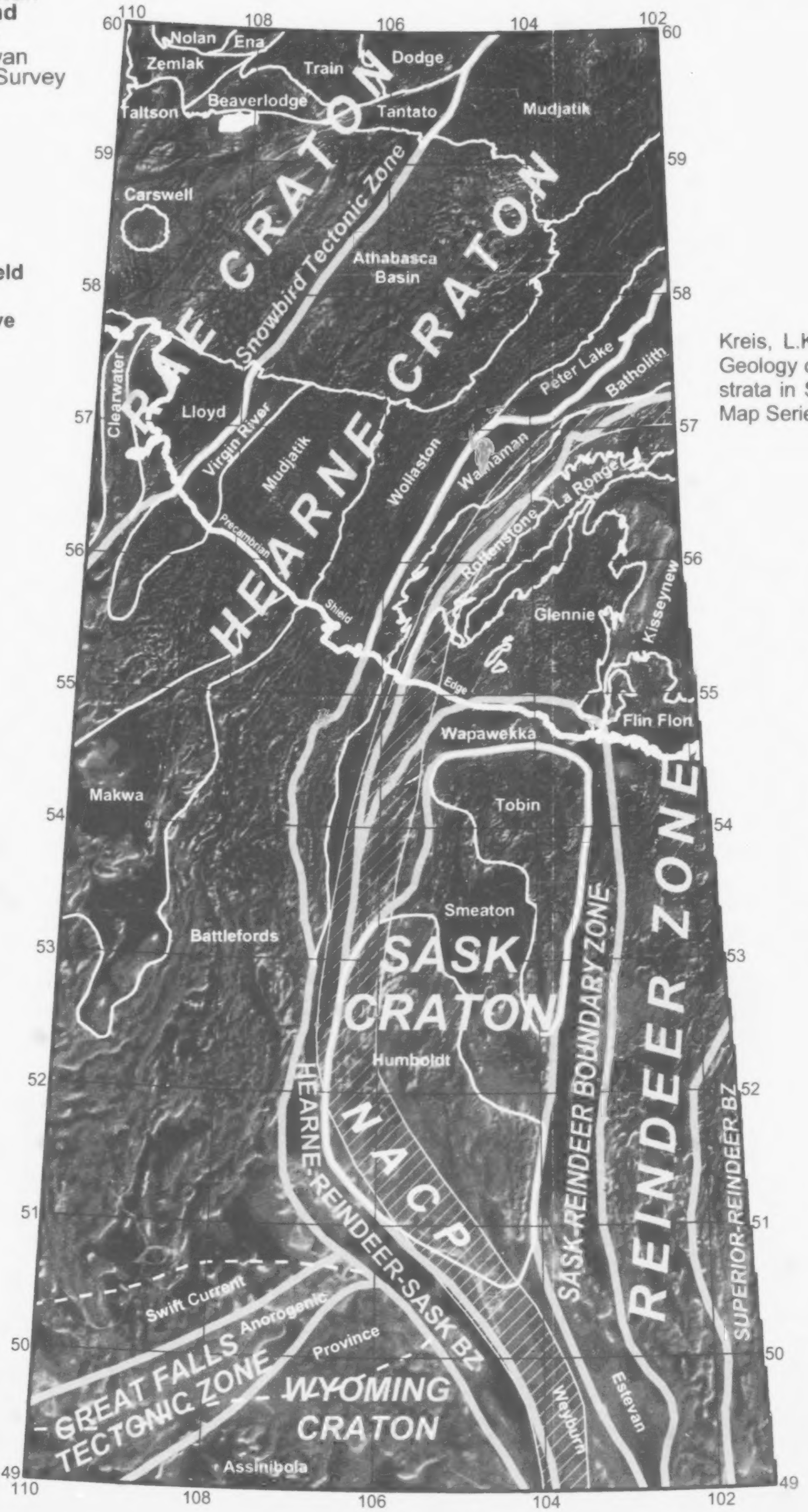
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HEARNE CRATON
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Province
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Assiniboia

Interpretive Geophysical Maps of Saskatchewan

Source of Data for
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Kreis, L.K., Ashton, K.E., and Maxeiner, R.O. (2000): Geology of the Precambrian basement and Phanerozoic strata in Saskatchewan; Sheet 1 of 8, Lower Paleozoic Map Series, Sask. Energy Mines, Open File Rep. 2000-2.

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SASKATCHEWAN 1948 GEOLOGICAL SURVEY

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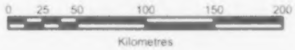
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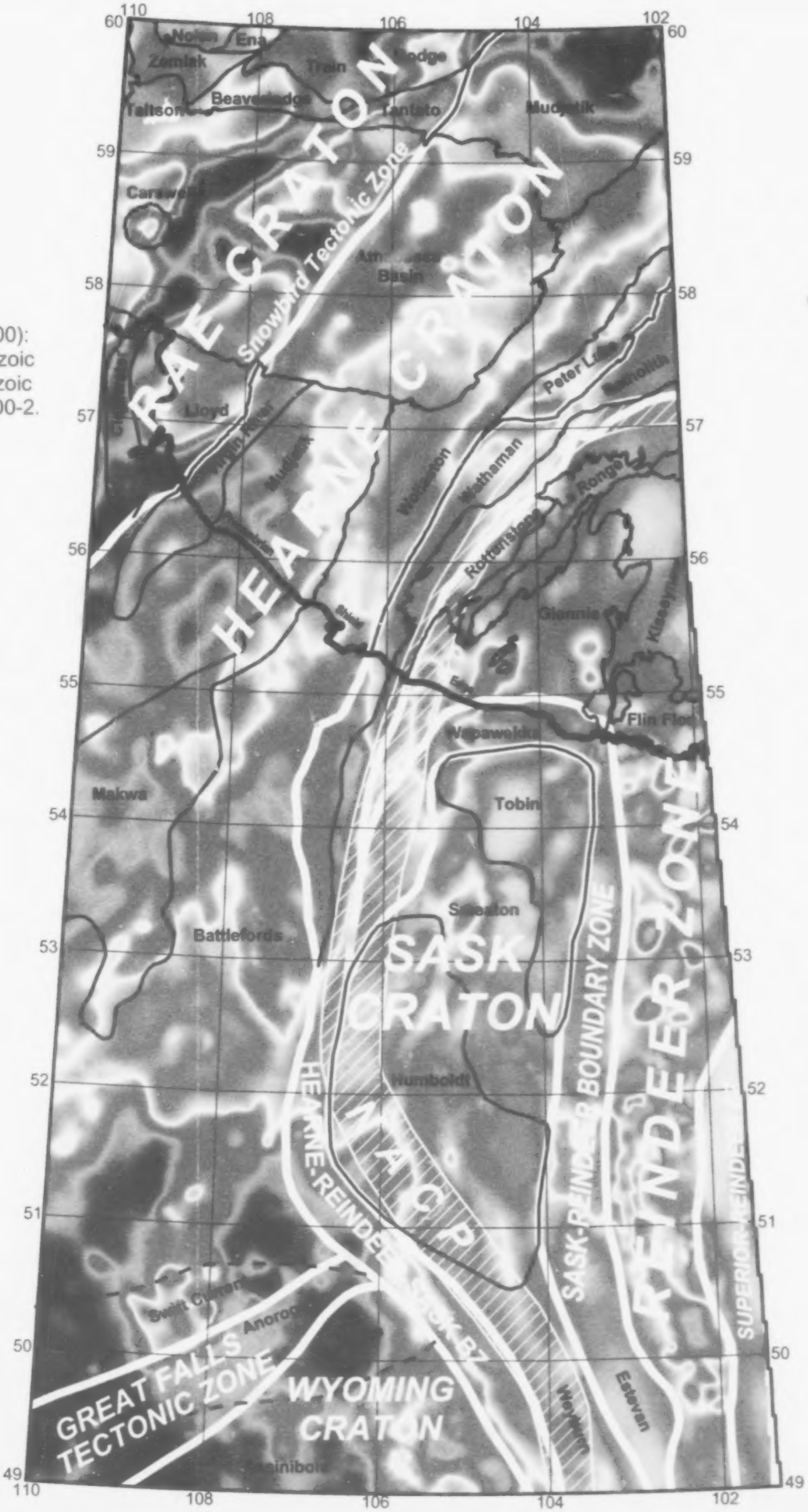
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Bouguer Gravity Anomaly Map

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Saskatchewan Industry and Resources
Saskatchewan Geological Survey

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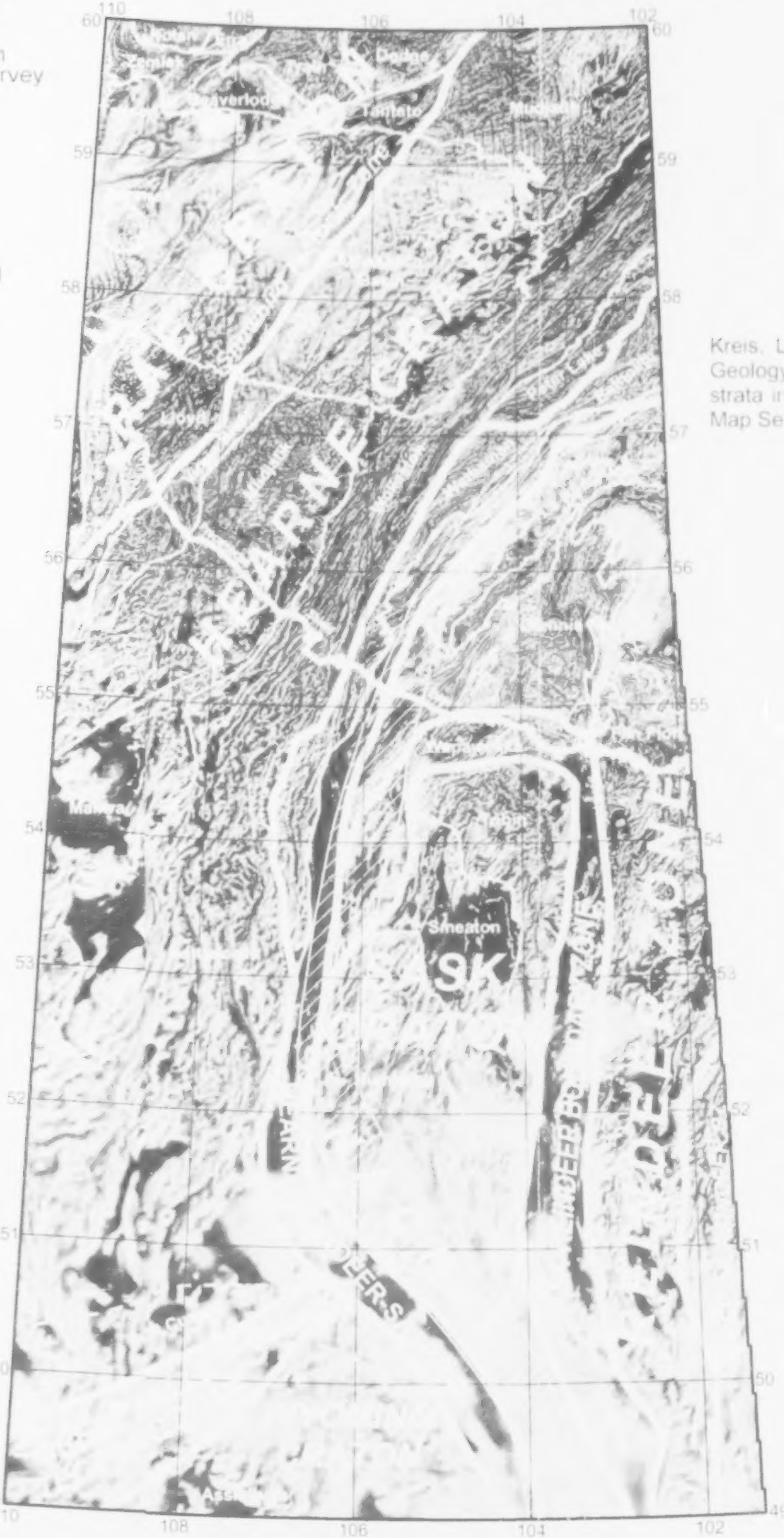
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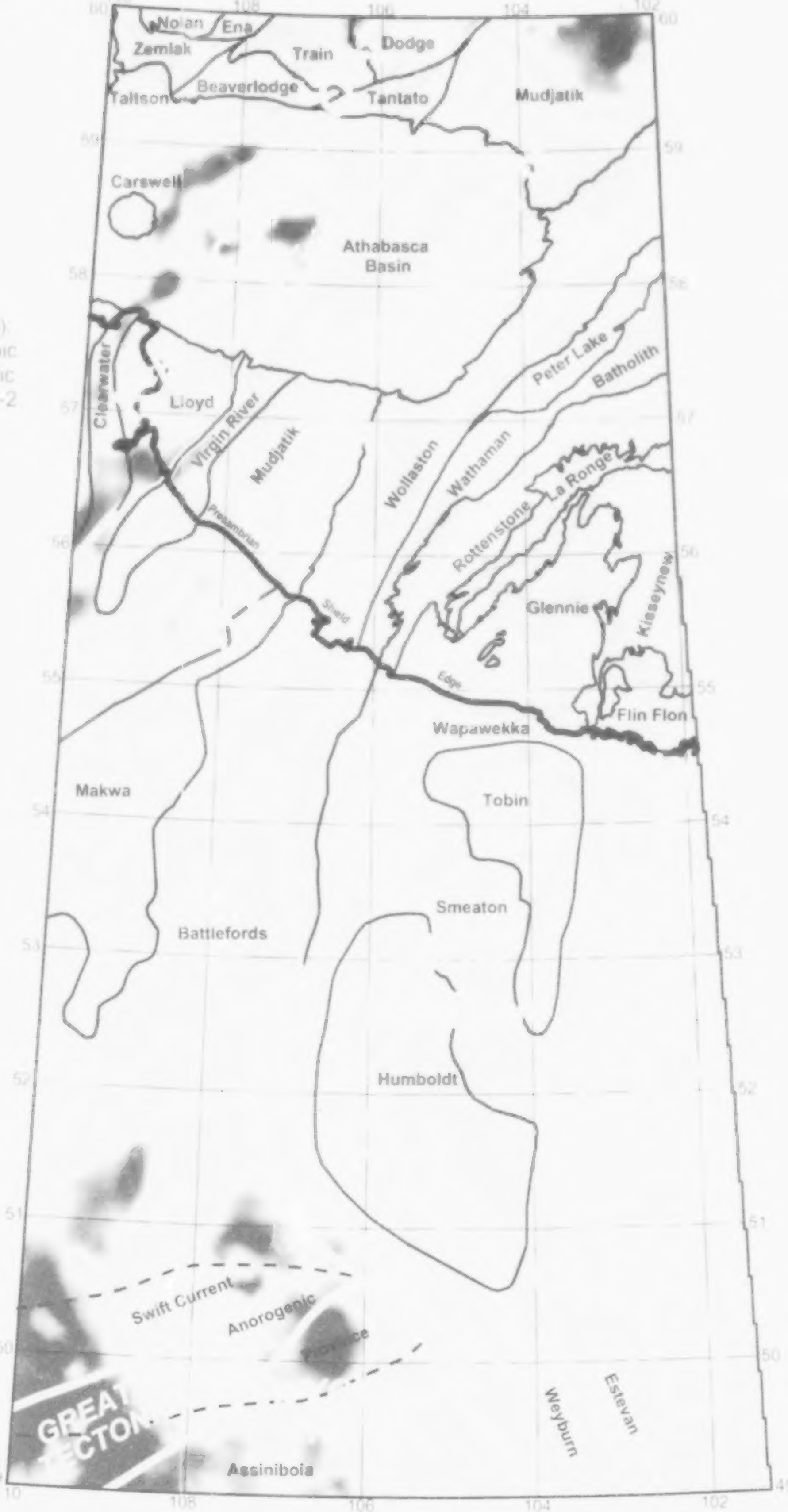
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Bouguer Gravity Anomaly Map

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Saskatchewan
Industry and
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Stratigraphic Correlation Chart

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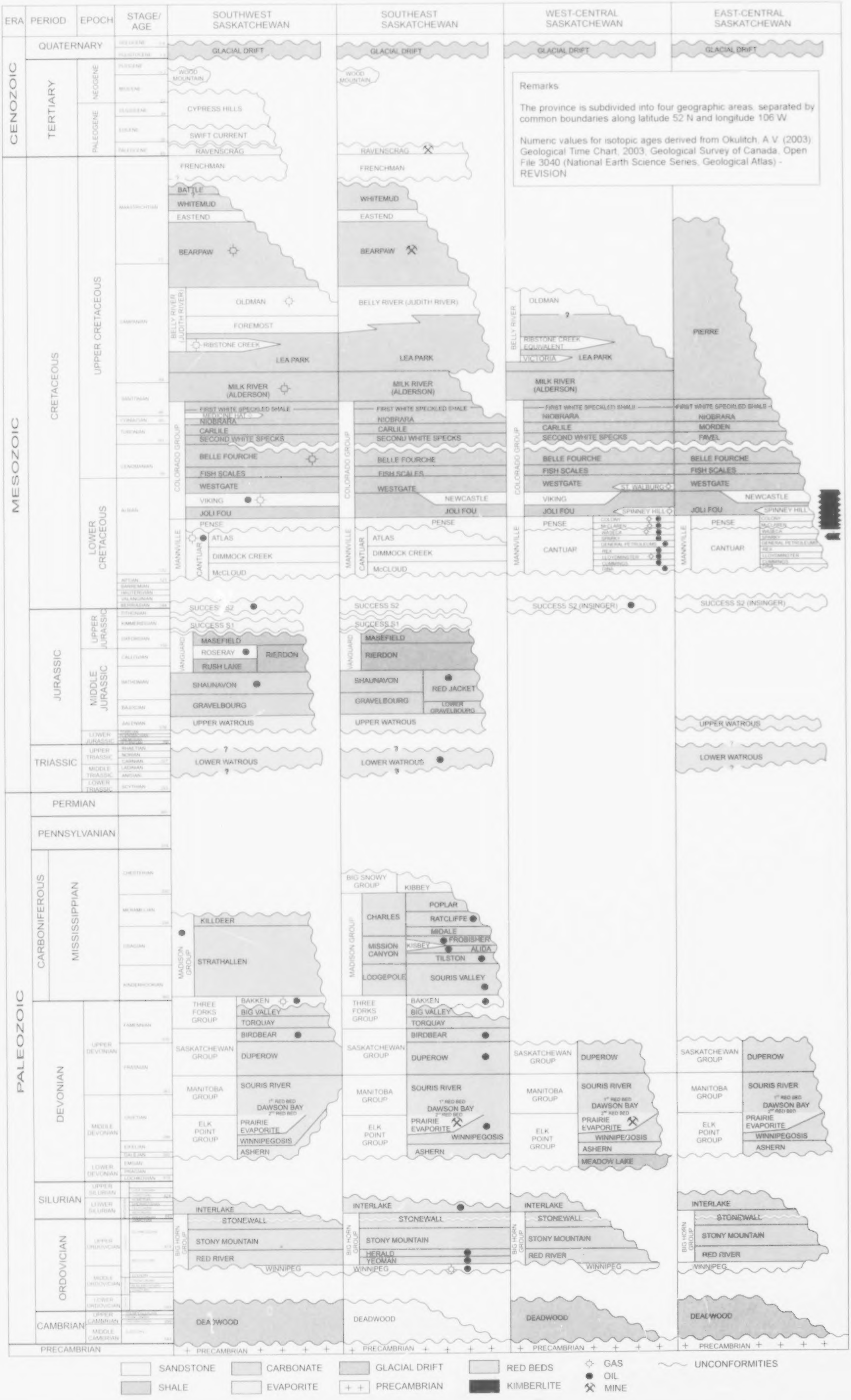

Remarks

The province is subdivided into four geographic areas, separated by common boundaries along latitude 52 N and longitude 106 W.

Numeric values for isotopic ages derived from Okulitch, A.V. (2003): Geological Time Chart, 2003; Geological Survey of Canada, Open File 3040 (National Earth Science Series, Geological Atlas) - REVISION

Saskatchewan
Industry and
Resources

Stratigraphic Correlation Chart

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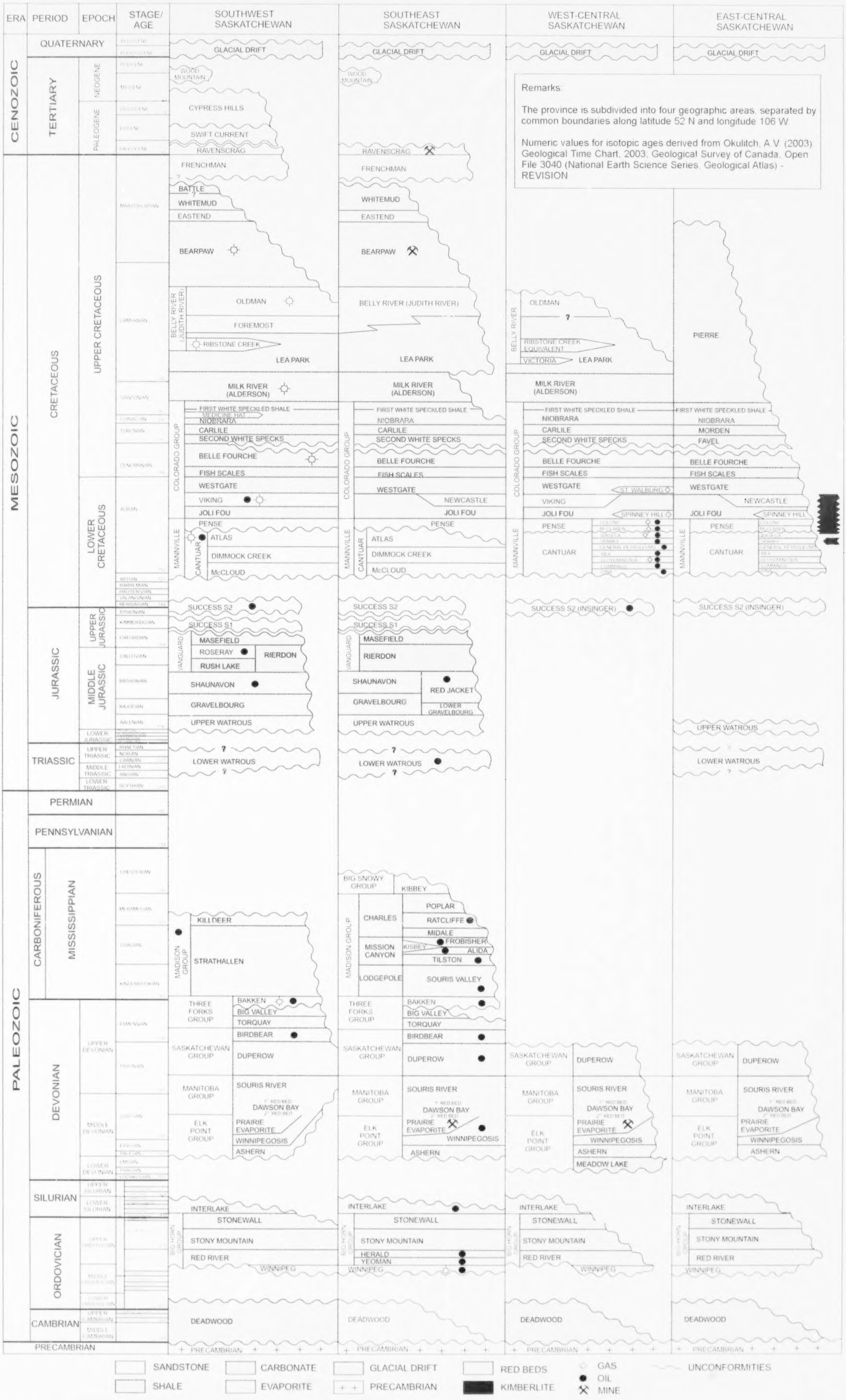
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OLDMAN
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RIBSTONE CREEK EQUIVALENT
VICTORIA
LEA PARK
PIERRE
MILK RIVER (ALDERSON)
COLORADO GROUP
FIRST WHITE SPECKLED SHALE
MEDICINE HAT
NIOBRARA
CARLILE
MORDEN
FAVEL
SECOND WHITE SPECKS
BELLE FOURCHE
FISH SCALES
WESTGATE
ST. WALBURG
NEWCASTLE
VIKING
JOLI FOU
SPINNEY HILL
PENSE
MANNVILLE
CANTUAR
ATLAS
DIMMOCK CREEK
McCLOUD
COLONY
McLAREN
WASECA
SPARKY
GENERAL PETROLEUM
REX
LLOYDMINSTER
CUMMINGS
DINA
SUCCESS S2
SUCCESS S2 (INSINGER)
SUCCESS S1
VANGUARD
MASEFIELD
ROSERAY
RUSH LAKE
RIERDON
SHAUNAVON
RED JACKET
GRAVELBOURG
LOWER GRAVELBOURG
UPPER WATROUS
LOWER WATROUS
?
BIG SNOWY GROUP
KIBBEY
MADISON GROUP
KILLDEER
STRATHALLEN
CHARLES
POPLAR
RATCLIFFE
MIDALE
FROBISHER
KISBEY
ALIDA
MISSION CANYON
TILSTON
LODGEPOLE
SOURIS VALLEY
THREE FORKS GROUP
BAKKEN
BIG VALLEY
TORQUAY
BIRDBEAR
SASKATCHEWAN GROUP
DUPEROW
MANITOBA GROUP
SOURIS RIVER
1ST RED BED
DAWSON BAY
2ND RED BED
ELK POINT GROUP
PRAIRIE EVAPORITE
WINNIPEGOSIS
ASHERN
MEADOW LAKE
INTERLAKE
BIG HORN GROUP
STONEWALL
STONY MOUNTAIN
RED RIVER
HERALD
YEOMAN
WINNIPEG
DEADWOOD
PRECAMBRIAN
SANDSTONE
SHALE
CARBONATE
EVAPORITE
GLACIAL DRIFT
PRECAMBRIAN
RED BEDS
KIMBERLITE
◇ GAS
● OIL
⚒ MINE
UNCONFORMITIES

Remarks:

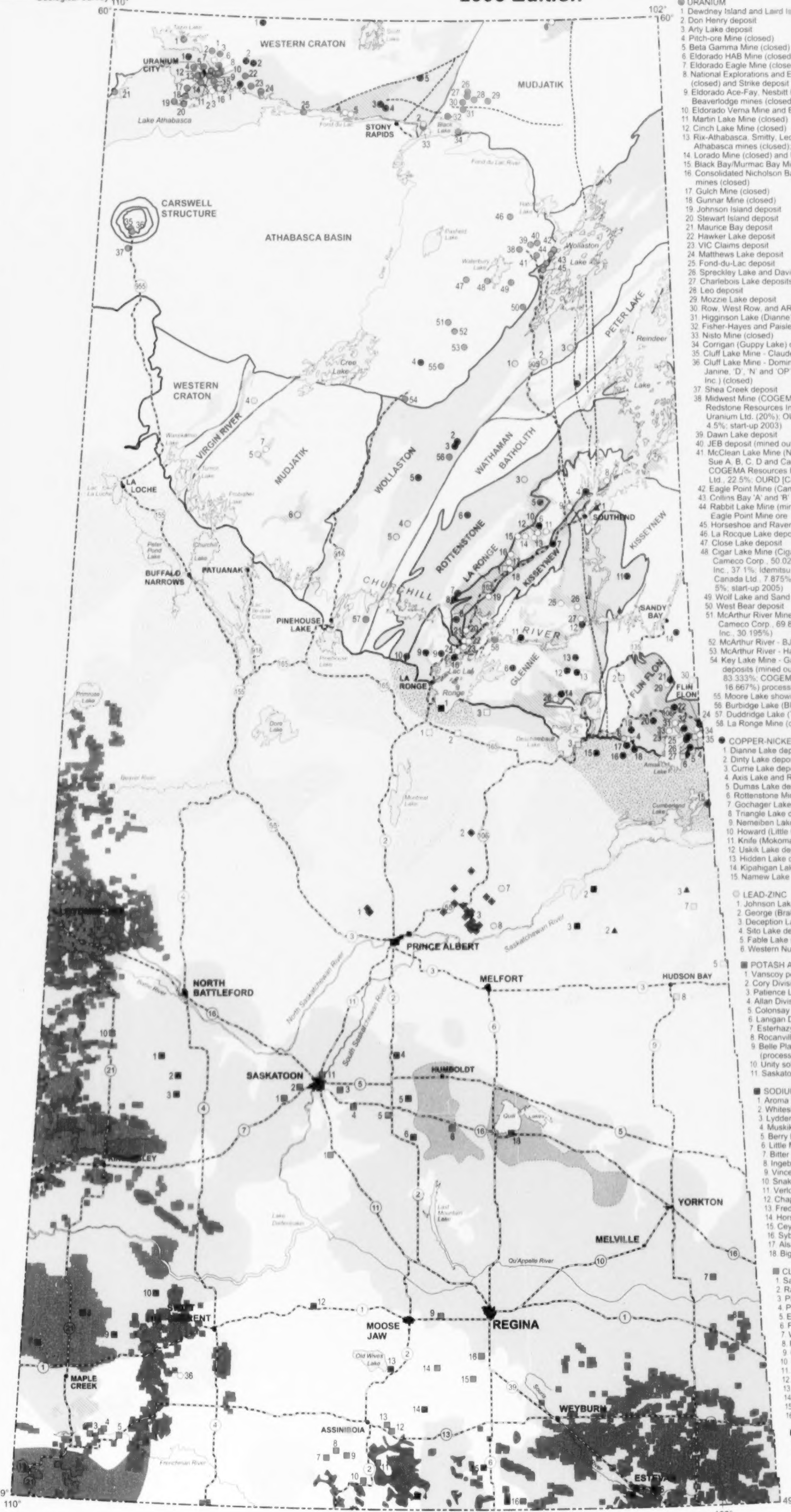
The province is subdivided into four geographic areas, separated by common boundaries along latitude 52 N and longitude 106 W.

Numeric values for isotopic ages derived from Okulitch, A.V. (2003): Geological Time Chart, 2003; Geological Survey of Canada, Open File 3040 (National Earth Science Series, Geological Atlas) - REVISION

Saskatchewan Industry and Resources
Saskatchewan Geological Survey

MINERAL RESOURCE MAP OF SASKATCHEWAN

2003 Edition



LEGEND

- □ Uranium potential
- □ Base metal potential
- □ Gold potential
- □ Diamond potential
- □ Major peat resource potential
- ■ Carbon dioxide (CO_2) resource potential
- ■ Oil fields
- ■ Gas fields
- ■ Coal fields
- □ Potash and salt resource areas
- ■ Carnallitic regions (magnesium)

SYMBOLS

- Edge of Precambrian Shield
- Precambrian domain boundaries and names
- Major bounding shear zones
- Major faults
- Roads
- Cities
- Towns

SCALE

25 0 25 50 75 Kilometers

25 0 25 50 Miles

Although the Department of Industry and Resources has exercised all reasonable care in the compilation, interpretation, and production of this map, it is not possible to ensure total accuracy, and all persons who rely on the information contained herein do so at their own risk. The Department of Industry and Resources and the Government of Saskatchewan do not accept liability for any errors, omissions, or inaccuracies that may be included in, or derived from, this map.

Precambrian Shield information compiled by:
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Phanerozoic Basin information compiled by:
L.I. Kelley and L.K. Kreis.
GIS and digital cartography by: W.L. Slimmon.
CAD by: L. Borisinkoff.
Copy editing by: C.L. Brown.

This map is available from:
Saskatchewan Industry and Resources
Publications Office
2101 Scarth Street
Regina, SK Canada S4P 3V7

KEY TO NUMBERED MINERAL DEPOSITS[†]

● URANIUM
1. Dewdney Island and Laird Island deposits
2. Don Henry deposit
3. Arty Lake deposit
4. Pitch-ore Mine (closed)
5. Beta Gamma Mine (closed)
6. Eldorado HAB Mine (closed) and Baska prospect
7. Eldorado Eagle Mine (closed) and ABC deposit
8. National Explorations and Eldorado Dubyna mines (closed) and Strike deposit
9. Eldorado Ace-Fay, Nesbitt Labine (Eagle-Ace), and Beaverlodge mines (closed)
10. Eldorado Verna Mine and Bolger Open Pit (closed)
11. Martin Lake Mine (closed)
12. Cinch Lake Mine (closed)
13. Rix-Athabasca, Smitty, Leonard, and Cayzor Athabasca mines (closed); St. Michael deposit
14. Lorado Mine (closed) and Uranium Ridge deposit
15. Black Bay/Murmac Bay Mine (closed)
16. Consolidated Nicholson Bay and Fish Hook Bay mines (closed)
17. Gulch Mine (closed)
18. Gunnar Mine (closed)
19. Johnson Island deposit
20. Stewart Island deposit
21. Maurice Bay deposit
22. Hawker Lake deposit
23. VIC Claims deposit
24. Matthews Lake deposit
25. Fond-du-Lac deposit
26. Spreckley Lake and David deposits
27. Charlebois Lake deposits
28. Leo deposit
29. Mozzie Lake deposit
30. Row, West Row, and ART deposits
31. Higginson Lake (Dianne) deposit
32. Fisher-Hayes and Paisley Lake deposits
33. Nisto Mine (closed)
34. Corrigan (Guppy Lake) deposit
35. Cluff Lake Mine - Claude deposit (mined out)
36. Cluff Lake Mine - Dominique-Peter, Dominique-Janine, 'D', 'N' and 'OP' deposits (COGEMA Res. Inc.) (closed)
37. Shea Creek deposit
38. Midwest Mine (COGEMA Resources Inc., 54.8%; Redstone Resources Inc., 20.7%; Tenwest Uranium Ltd. (20%); OURD [Canada] Co. Ltd., 4.5%; start-up 2003)
39. Dawn Lake deposit
40. JEB deposit (mined out)
41. McClean Lake Mine (North and South deposits; Sue A, B, C, D and Caribou Lake deposits; COGEMA Resources Inc., 70%; Denison Mines Ltd., 22.5%; OURD [Canada] Co. Ltd., 7.5%)
42. Eagle Point Mine (Cameco Corp.)
43. Collins Bay 'A' and 'B' Zone deposits (mined out)
44. Rabbit Lake Mine (mined out); mill processing Eagle Point Mine ore
45. Horseshoe and Raven deposits
46. La Rocque Lake deposit
47. Close Lake deposit
48. Cigar Lake Mine (Cigar Lake Mining Corp. = Cameco Corp., 50.025%; COGEMA Resources Inc., 37.1%; Idemitsu Uranium Exploration Canada Ltd., 7.875%; TEPCO Resources Inc., 5%; start-up 2005)
49. Wolf Lake and Sand Lake deposits
50. West Bear deposit
51. McArthur River Mine (P2 Zone deposit; Cameco Corp., 69.805%; COGEMA Resources Inc., 30.195%)
52. McArthur River - BJ Zone deposit
53. McArthur River - Harrigan Zone deposit
54. Key Lake Mine - Gaertner and Deilmann deposits (mined out); mill (Cameco Corp., 83.333%; COGEMA Resources Inc., 16.667%) processing McArthur River Mine ore
55. Moore Lake showing
56. Burbidge Lake (BURR) deposit
57. Duddridge Lake (Thor) deposit
58. La Ronge Mine (closed)

● COPPER-NICKEL AND COPPER-COBALT
1. Dianne Lake deposit
2. Dinty Lake deposit
3. Currie Lake deposit
4. Axis Lake and Rea Lake deposits
5. Dumas Lake deposit
6. Rottenstone Mine (closed)
7. Gochager Lake deposit
8. Triangle Lake deposit
9. Nemeiben Lake (Dunlop) deposit
10. Howard (Little Clam) Lake deposit
11. Knife (Mokoman) Lake deposit
12. Uskik Lake deposit
13. Hidden Lake deposit
14. Kipahigan Lake deposit
15. Namew Lake Mine (closed) (in Manitoba)

○ LEAD-ZINC
1. Johnson Lake (Marina) showing
2. George (Brakewell) Lake deposit
3. Deception Lake showing
4. Sito Lake deposits
5. Fable Lake showing
6. Western Nuclear Mine (closed)

○ GOLD
1. Neeley Lake deposit
2. Box Mine (closed) and deposit
3. Athona Mine (closed) and deposit and Greenlee/Anderson deposit
4. ELA deposit
5. Camille Bay deposits
6. Nirdac Creek showing
7. Ithingo Lake deposit
8. Rosie and Narrow Lake showings
9. Fleming Lake showing
10. Twin Zone and Wedge Lake deposits
11. Weedy Lake and Golden Heart deposits
12. Komis Mine (closed) and EP deposit
13. Corner Lake (Augustus) deposit and Oven Lake showing
14. Tower East and West deposits
15. Kaslo, Centre, and Narrow deposits
16. Jojay deposit
17. Star Lake and Jolu mines (closed) and Rod, Mallard, and Rush Zones (mined out)
18. Jasper Mine (closed) (Fork Lakes, Tamar, and Transom deposits)
19. Greywacke deposit
20. North Lake deposit
21. Contact Lake (Bakos zone) Mine (closed)
22. Preview North and South, PAP A, B, and C deposits
23. Sulphide Lake deposits
24. Lynx Lake (GEM) deposit
25. Seabee Mine (Claude Resources Inc.) and Boundary Zone deposit (ore milled at Seabee Mine) (Claude Resources Inc. and Currie Rose Resources)
26. Santoy Lake showings
27. Georges Lake showings
28. Brownell Lake showings
29. Manson Bay (Schotts Lake) deposit
30. Eccles Lake (Dolly) deposit
31. Graham Mine (closed) and deposit
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33. Prince Albert (Monarch) Mine (closed) and Laural Lake deposit
34. Newcor, Bootleg (Rio), and Henning-Maloney mines (closed)
35. Phantom Lake and McMillan mines
36. Simmie paleoplacer showing

● COPPER-ZINC
1. Campbell River showings
2. Janice Lake showings
3. Jansem showings
4. Stackhouse Bay showing
5. Elephant Lake deposit
6. Discovery Lake deposits
7. Brabant Lake PEG/McKenzie deposit
8. Borys Lake deposit
9. Elizabeth Lake deposit
10. Anglo-Rouyn Mine (closed)
11. Pitching Lake deposit
12. SAD Zone (HBED Zone) deposit
13. Hook Lake (Gee Lake) deposit
14. Brownell Lake deposit
15. Bigstone Lake deposit
16. Miskat Lake deposit
17. McIlvenna Bay deposit
18. McDermott Lake (Balsam Zone) deposit
19. Ramsay (Quandt/Keputch) deposit
20. FON Zone deposit
21. Schotts Lake deposit
22. Otonadah Lake deposit
23. Black Prince showing
24. Flin Flon Mine (closed) and Callinan Mine (Hudson Bay Mining and Smelting Co. Ltd.)
25. Birch Lake and Flexar mines (closed)
26. Konuto Lake Mine (Hudson Bay Mining and Smelting Co. Ltd.)
27. Coronation Mine (closed)

○ IRON FORMATION
1. Fish Hook Bay showing
2. Triana deposit
3. Spence Lake showing
4. Nyberg Lake (VH) deposit
5. Ithingo Lake showing
6. Dot Lake showing
7. Kelsey Lake deposit
8. Choiceland deposit

● RARE EARTH OCCURRENCES
1. Nisikkatch Lake - Hoidas Lake
2. Alces Lake
3. Archie Lake (+ uranium)
4. Maw Zone (+ uranium)
5. Kulyk Lake (+ uranium)
6. Jahala Lake (+ uranium)

◆ KIMBERLITE OCCURRENCES
1. Sturgeon Lake
2. Candle Lake
3. Fort à la Corne kimberlite field

▲ MISCELLANEOUS OCCURRENCES
1. Deep Bay graphite deposit
2. Pasquia Hills oil shale deposit
3. Bainbridge River nodular manganese

■ POTASH AND SALT
1. Vanscoy potash mine (Agrium Inc.)
2. Cory Division potash mine (Potash Corp. of Sask. Inc.) (by-product $CaCl_2$ brine)
3. Patience Lake Division potash solution mine (Potash Corp. of Sask. Inc.)
4. Allan Division potash mine (Potash Corp. of Sask. Inc.)
5. Colonsay potash mine (I.M.C. Kalium Inc.)
6. Lanigan Division potash mine (Potash Corp. of Sask. Inc.)
7. Esterhazy K-1 and K-2 potash mines (I.M.C. Kalium Inc.)
8. Rocanville Division potash mine (Potash Corp. of Sask. Inc.)
9. Belle Plaine potash solution mine (I.M.C. Kalium Inc.) and fine salt plant (processes waste salt from potash mine) (Canadian Salt Co. Ltd.)
10. Unity solution salt mine and plant (Sifto Canada Inc.)
11. Saskatoon chloride based chemical plant (Sterling Pulp Chemicals)

■ SODIUM SULPHATE AND POTASSIUM SULPHATE
1. Aroma Lake sodium sulphate deposit
2. Whiteshore Lake sodium sulphate plant (Millar Western Industries Ltd.)
3. Lydden Lake sodium sulphate deposit
4. Muskiki Lake sodium sulphate deposit
5. Berry Lake sodium sulphate deposit
6. Little Manitou Lake sodium sulphate deposit
7. Bitter Lake sodium sulphate deposit
8. Ingebrigt Lake sodium sulphate plant (closed)
9. Vincent Lake sodium sulphate deposit
10. Snakehole Lake sodium sulphate plant (closed)
11. Verlo East sodium sulphate deposit
12. Chaplin Lake sodium sulphate plant (Saskatchewan Minerals)
13. Frederick Lake (Bishopric) sodium sulphate plant (closed)
14. Horseshoe (Shoe) Lake sodium sulphate plant (closed)
15. Ceylon Lake (Salt Lake) sodium sulphate deposit
16. Sybouts East (East Coteau Lake) sodium sulphate plant (closed)
17. Alsask Lake potassium sulphate plant (Potasium Sulphate Co. Alsask Inc.)
18. Big Quill Lake potassium sulphate plant (Big Quill Resources)

■ CLAY RESOURCES
1. Saskatoon clay quarry and plant (Cindercrete Products Ltd.)
2. Ravenscrag clay quarry (brick) (IXL Industries Ltd.)
3. PR-1 clay quarry (stoneware) (Plainsman Clays)
4. PR-3 clay quarry (stoneware) (Plainsman Clays)
5. Eastend clay quarry
6. Frenchman clay prospect
7. Wood Mountain - Fir Mountain kaolin prospect
8. Flintoft clay pit (refractory and ball clay) (closed)
9. Gollier Creek kaolin deposit
10. Rockglen clay pit (brick clay) (IXL Industries Ltd.)
11. St. Victor bentonite deposit (swelling bentonite)
12. Readlyn ball clay deposit
13. Willows clay pit (refractory and ball clay)
14. A.P. Green Claybank brick plant (closed)
15. Truax bentonite quarry (stoneware) (Canadian Clay Products Inc.)
16. Wilcox bentonite plant (Canadian Clay Products Inc.)

■ COAL AND PEAT
1. Lac La Ronge lignite (sub-bituminous) deposit
2. Carrot River Peat Moss Mine (Premier Sask. Inc.)
3. Carrot River peat moss plant (Premier Sask. Inc.)
4. Poplar River mine (Luscar Ltd.)
5. Boundary Dam (Shand, Costello, and Utility) Mine (Luscar Ltd.)
6. Bienfait Mine (Luscar Ltd.)

□ BUILDING MATERIALS
1. Neyrink Lake black and grey granite (diorite) building stone
2. Sahli green granite building stone
3. Deschambault marble (dolomite) quarry (Graham Construction and Engineering (1985) Ltd.)
4. Mystic Lake "Verde Antique" marble (veined amphibolite) building stone
5. McNally Lake buckskin marble (dolomite) building stone
6. Amisk Lake red marble (dolomite) building stone
7. Waskwei River cement rock deposit
8. Hudson Bay cement rock deposit

□ SILICA SAND
1. Bow River silica sand deposit
2. Nipekamew River silica sand deposit
3. Wappawekka Lake silica sand deposit
4. Hanson Lake silica sand deposit
5. Red Deer River silica sand quarry (Red Deer Silica)

[†] Mine = Past, present, and test producing mines
Deposit = Deposits (calculated reserves) and developed prospects (drilling delineated mineralization)
Showing = Mineral occurrence with assays

Saskatchewan
Industry and
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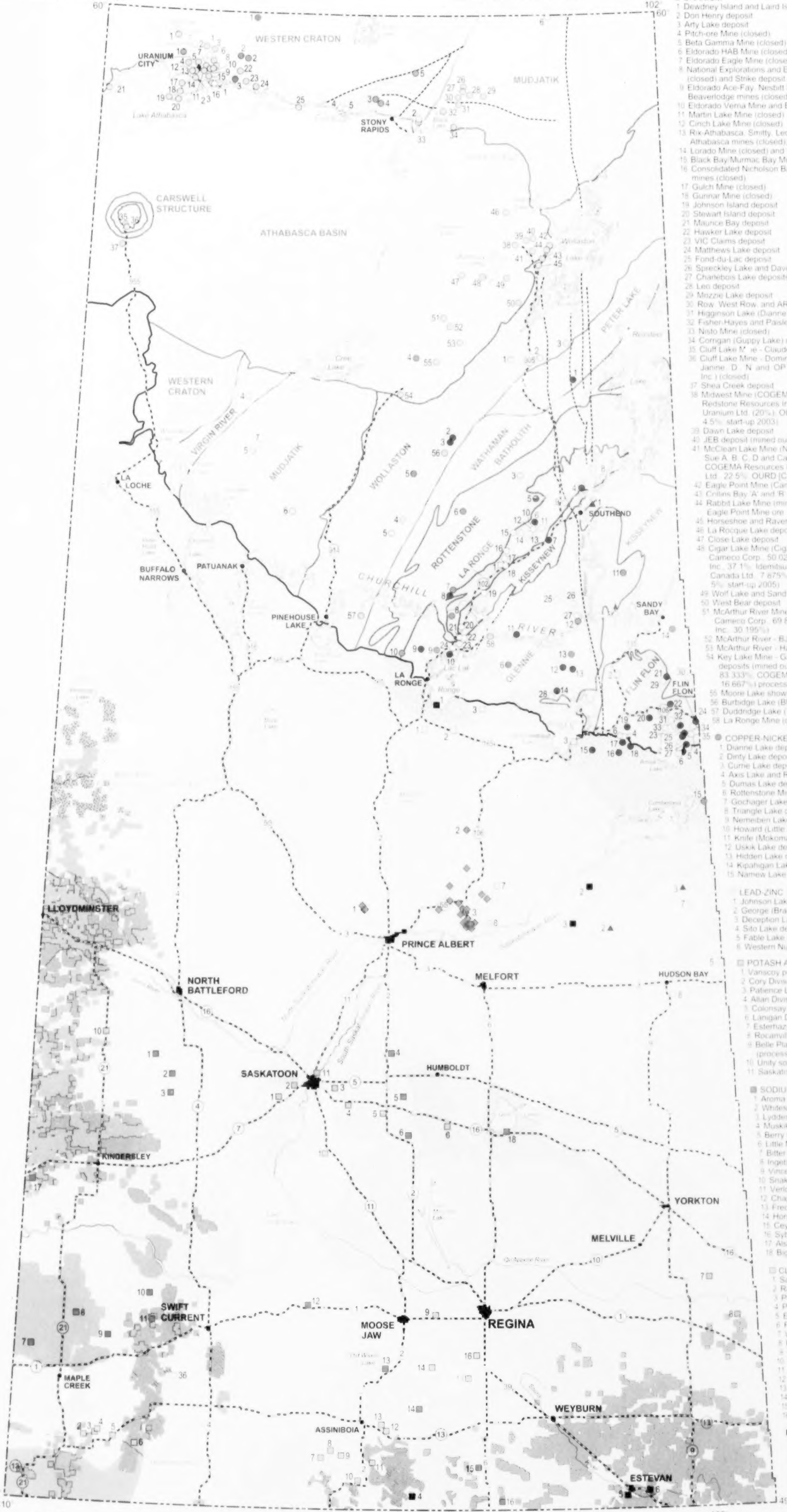
Saskatchewan
Geological Survey

MINERAL RESOURCE MAP OF SASKATCHEWAN

2003 Edition



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1 Dewdney Island and Laird Island deposits
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9 Eldorado Ace-Fay, Nesbitt Labine (Eagle-Ace), and Beaverlodge mines (closed)
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11 Martin Lake Mine (closed)
12 Cinch Lake Mine (closed)
13 Rix-Athabasca, Smitty, Leonard, and Cayzor Athabasca mines (closed); St. Michael deposit
14 Lorado Mine (closed) and Uranium Ridge deposit
15 Black Bay/Murmac Bay Mine (closed)
16 Consolidated Nicholson Bay and Fish Hook Bay mines (closed)
17 Gulch Mine (closed)
18 Gunnar Mine (closed)
19 Johnson Island deposit
20 Stewart Island deposit
21 Maurice Bay deposit
22 Hawker Lake deposit
23 VIC Claims deposit
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26 Spreckley Lake and David deposits
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6 Frenchman clay prospect
7 Wood Mountain - Fir Mountain kaolin prospect
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9 Gollier Creek kaolin deposit
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5 Boundary Dam (Shand, Costello, and Utility) Mine (Luscar Ltd.)
6 Bienfait Mine (Luscar Ltd.)

GOLD
1 Neeley Lake deposit
2 Box Mine (closed) and deposit
3 Athona Mine (closed) and deposit and Greenlee/Anderson deposit
4 ELA deposit
5 Camille Bay deposits
6 Nirdac Creek showing
7 Ithingo Lake deposit
8 Rose and Narrow Lake showings
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23 Black Prince showing
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27 Coronation Mine (closed)

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2 Triana deposit
3 Spence Lake showing
4 Nyberg Lake (VH) deposit
5 Ithingo Lake showing
6 Dot Lake showing
7 Kelsey Lake deposit
8 Choiceland deposit

● RARE EARTH OCCURRENCES
1 Nisikkatch Lake - Hoidas Lake
2 Alces Lake
3 Archie Lake (+ uranium)
4 Maw Zone (+ uranium)
5 Kulyk Lake (+ uranium)
6 Jahala Lake (+ uranium)

◆ KIMBERLITE OCCURRENCES
1 Sturgeon Lake
2 Candle Lake
3 Fort à la Corne kimberlite field

▲ MISCELLANEOUS OCCURRENCES
1 Deep Bay graphite deposit
2 Pasquia Hills oil shale deposit
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Deposit = Deposits (calculated reserves) and developed prospects (drilling delineated mineralization)
Showing = Mineral occurrence with assays

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